CRANFIELD UNIVERSITY

HARRIET EMKES

A decision support tool for landfill methane generation.

School of Applied Sciences

MSc by Research
Academic Year: 2012 - 2013

Supervisor: Dr Frédéric Coulon and Dr Stuart Wagland
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ABSTRACT

This paper focuses on providing a decision support tool (DST) to enhance methane generation at individual landfill sites. To date there is no decision support tool (DST) available to provide landfill decision makers with clear and simplified information for decision makers to understand what is happening within a landfill site, to assess its performance and to be aware of potential remedies to any issues. The current lack in understanding stems from the complexity of the landfill waste degradation process. Two scoring sets for landfill gas production performance are calculated with the tool including (1) methane output score which measures the deviation of the actual methane output rate at each site which the prediction generated by the first order decay model LandGEM; and (2) landfill gas indicators' score which measures the deviation of the landfill gas indicators from their individual ideal ranges for optimal methane generation conditions. Landfill gas indicators selected include moisture content, temperature, alkalinity, pH, BOD, COD, BOD/COD ratio, ammonia, chloride, iron and zinc. A total landfill gas indicator score is also provided using multi-criteria analysis to calculate the sum of weighted scores for each indicator. The weights for each indicator are calculated using the analytical hierarchical process. The tool is tested against five scenarios for landfill sites with a range of good, average and poor landfill methane generation in one year, 2012. An interpretation of the results is given for each scenario and recommendations are highlighted for methane output rate enhancement. The scenarios used clearly illustrated how the tool can be easily used by landfill operators to enhance their understanding of methane generation at a site-specific level. The tool assists the landfill operator to track landfill methane generation over time, compare and rank sites and identify problems areas within a landfill site.

Keywords: Multi-criteria analysis, landfill assessment, landfill gas indicators, methane generation, waste management.

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AHP	Analytical Hierarchical Process
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DST	Decision Support Tool
E-PRTR	European Pollutant Release and Transfer Register
IPCC	Intergovernmental Panel on Climate Change
LandGEM	Landfill Gas Emissions Model
LCFA	Long Chain Fatty Acid
MCA	Multi-criteria analysis
MSW	Municipal Solid Waste
US EPA	United States Environment Protection Agency
VFA	Volatile Fatty Acid

GLOSSARY OF TERMS

Anaerobic Digestion	The biodegradation of organic material by microorganisms in the absence of oxygen to produce methane and carbon dioxide gas. The biodegradation takes place through a number of stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis.
Analytical Hierarchical Process	An MCA approach to mathematically define preferences for a set of criteria/indicators. This technique is used to provide weightings for the importance of each criterion on the pre-assigned objective of the MCA (Saaty, 1980). The user must define how much more important one criterion is over another on a scale of 1-9 in a series of pairwise comparisons. The question prescribed is “How many more times more important is criteria A over criteria B?” Reciprocal values are used automatically for the reverse comparison of criteria i.e. B over A.
Decay rate constant (k)	The decay rate constant determines the rate of release of the methane potential within a landfill site in first order decay models such as LandGEM. It is a function of environmental conditions within the landfill such as pH, temperature and moisture. Within the models its value remains constant over time.
Decision support tool	Decision support tools are “documents or software produced with the aim of supporting decision making i.e., something that carries out a process in decision making” (Bardos et al., 2002).They provide a robust, consistent, transparent and reproducible method for the decision making process (Sorvari and Seppälä, 2010).
Ideal Value	The value or range of values of a specific waste, gas or leachate parameter within which methane output from landfill sites is expected to be optimised.
Indicator	One of a set of measures to assess the achievement of the overall objective.
Landfill Gas	The product of the biodegradation of waste in landfills. The gas consists mainly of carbon dioxide and methane but also contains nitrogen and other trace gases.

Landfill Gas Indicator Score	This score provides an indication how far the landfill gas indicator values within the landfill environment varies from the ideal range for each indicator to produce an optimal methane output rate. The weighted sum of the percentage deviation of the actual indicator value from the average ideal value of that indicator relative to the range of the ideal value at the specified point in time.
Landfill methane generation	Within this paper, landfill methane generation is defined as methane output rate achieved by a landfill site. Methane is used as the most valuable product of landfill processes to a landfill operator. Two scores are used to measure landfill methane generation: the methane output score and the landfill gas indicator score.
Methane Output Score	This score provides an indication of how well a landfill site is producing methane gas. The percentage deviation of actual methane output rate from the predicted value for each landfill site at the specified point in time. The prediction in this DST is provided by LandGEM.
Multi-criteria analysis	Any method to analyse the preferences within a set of options to achieve one or multiple overall objectives. Often used when monetary data is unavailable or inappropriate.
Overall Objective	The overall goal of the MCA and against what each indicator is measured.
Potential Methane generation capacity(L_0)	The methane generation potential is a constant which determines the potential for a landfill site to produce methane. It has a positive relationship with the amount of cellulose present in the waste to biodegrade into methane.

A decision support tool for landfill methane generation.

Harriet Emkes[a], Frédéric Coulon[a1] and Stuart Wagland[a]

[a] *Department of Environmental Science and Technology, Cranfield University, College Road, Cranfield, Bedfordshire, MK43 0AL, United Kingdom.*

ABSTRACT

This thesis focuses on providing a decision support tool (DST) to enhance methane generation at individual landfill sites. To date there is no decision support tool (DST) available to provide landfill decision makers with clear and simplified information for decision makers to understand what is happening within a landfill site, to assess its performance and to be aware of potential remedies to any issues. The current lack in understanding stems from the complexity of the landfill waste degradation process. Two scoring sets for landfill gas production performance are calculated with the tool including (1) methane output score which measures the deviation of the actual methane output rate at each site which the prediction generated by the first order decay model LandGEM; and (2) landfill gas indicators' score which measures the deviation of the landfill gas indicators from their individual ideal ranges for optimal methane generation conditions. Landfill gas indicators selected include moisture content, temperature, alkalinity, pH, BOD, COD, BOD/COD ratio, ammonia, chloride, iron and zinc. A total landfill gas indicator score is also provided using multi-criteria analysis to calculate the sum of weighted scores for each indicator. The weights for each indicator are calculated using the analytical hierarchical process. The tool is tested against five scenarios for landfill sites with a range of good, average and poor landfill methane generation in one year, 2012. An interpretation of the results is given for each scenario and recommendations are highlighted for

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Abbreviations: AHP, analytical hierarchical process; BOD, biochemical oxygen demand; COD, chemical oxygen demand; DST, decision support tool; E-PRTR, European pollutant release and transfer register; LandGEM, landfill gas emissions model; MCA, multi-criteria analysis; US EPA, United States environment protection agency; VFA, volatile fatty acid.

[1] Corresponding author: Department of Environmental Science and Technology, Cranfield University, Cranfield, Bedfordshire, MK43 0AL, UK. Tel.: +44 01234 754981. E-mail address: f.coulon@cranfield.ac.uk (Dr F. Coulon).

methane output rate enhancement. The scenarios used clearly illustrated how the tool can be easily used by landfill operators to enhance their understanding of methane generation at a site-specific level. The tool assists the landfill operator to track landfill methane generation over time, compare and rank sites and identify problems areas within a landfill site.

Key Words: Multi-criteria analysis, landfill assessment, landfill gas indicators, methane generation, waste management.

1. Introduction

The improvement of the generation of methane for sale by landfill operators is hampered by a general lack in understanding of landfill processes at the field-scale (Cho et al., 2012). Difficulties in understanding derive from the heterogeneous nature of landfill waste, lack of access to the waste once deposited and the interpretation of a wide variety of landfill parameters. The causes of landfill gas fluctuations in the field therefore, largely continue to be unknown. Therefore, there is a need for clear, simplified method of integrating a wide range of data to understand how well a landfill site is performing in terms of methane output rate and what can be done to improve it.

Landfill operators are concerned with the cost of monitoring sites and the profit from the sale methane derived energy. Enhancing methane output increases the landfill operator’s revenues and offsets the cost of gas extraction system implementation, maintenance and operation. Electricity and heat produced from landfill gas can be sold for revenue as well as income from government incentives such as the feed in tariff, renewable obligation certificates and the renewable heat incentive. Strickland (2010) argues that this means that steady profit can be made in a relatively short period of time however costs for all factors involved vary widely and therefore estimates are not quoted here. However, there is a clear business case for improving landfill methane generation for existing sites.

There is currently no decision support tool used specifically for the assessment of landfill methane generation. The majority of tools for landfill sites focus on environmental risk management objectives in accordance with environmental regulations (Laner et al., 2012). Models are also available to predict landfill gas output such as LandGEM and GasSim (Golder Associates, 2013; US EPA, 2005) but these do not provide guidance as to what is problematic in the landfill or what can be done to increase gas production. However, there is a well-established literature base on multi-criteria analysis which can be applied to the case of landfill methane generation to assimilate a wide base of landfill gas parameters into a tool.

A decision support tool provides a robust, consistent, transparent and reproducible method for the decision making process (Sorvari and Seppälä, 2010). Multi criteria analysis is essential for the use of a decision support tool in a landfill situation due to the wide range of processes and parameters involved. It is a widely used and tested method in modern policy decision making such as deciding between which waste management technologies to use (Dodgson et al., 2009).

The aim of this research is to develop a decision support tool to enhance methane generation within individual landfill sites. The objectives are to:

1. Provide landfill decision makers with clear and simplified information on the state of a landfill site in terms of landfill gas production with reference to target values.
2. Develop a tool that highlights what problems exist within a landfill site.
3. Provide recommendations as to what can be done to enhance methane generation.
4. Provide supporting information about the tool to the user to understand its limitations and the assumptions made.
5. Provide the framework for a tool which can be improved over time as new data becomes available.

This paper presents a unique DST to assess landfill methane generation on a site-specific basis with two scores. The first score assesses the methane output produced over time compared to predictive model values. The second provides a breakdown of landfill gas indicators to assess the viability of the landfill environment to produce methane. Parameters include pH, ammonia and moisture content. This is achieved by comparing actual values for key indicators to previously recorded data. The user is then able to prioritise areas of management which can enhance landfill methane generation. The tool also provides suggestions for remedial action for issues with each indicator.

The paper is presented as a journal article to be submitted to the Waste Management journal, omitting the Literature Review section. Guidelines for this journal are provided in Appendix A.

2. Literature Review

Landfill remains a widely used waste management method both in the UK and abroad despite EU Landfill Directive (1999/31/EC) stipulations for significant reductions in BMW to landfill. An average of 50% of local authority collected waste was sent to landfill in 2010/11 in the UK compared to an average of 40% in the EU-27 (Department for Environment, Food and Rural Affairs, 2013). Even though commercial and industrial, construction and demolition and other categories are not included, local authority waste represents the majority of organic content in landfills. There is a lack of up to date research conducted on the effects of the Landfill Directive (1999/31/EC) in the UK on changing waste compositions and how this will affect degradation rates (kinetic constants), leachate quality and biogas output (Burnley et al., 2007; Burnley, 2007; Wagland et al., 2012; Cho et al., 2012; Kim and Townsend, 2012).

Improvement in the management of landfill sites provides benefits including increases in operator revenues through the sale of methane derived energy and through the reduction in time (and cost) necessary for site management as sites reach stabilisation. Also environmental concerns are addressed in terms of reducing landfills 40% contribution to methane greenhouse gas emissions and leachate pollution (Department for Environment, Food and Rural Affairs, 2007). These become increasingly important issues for UK landfill stakeholders as sites are closed but continue to produce emissions for indefinite periods of time (Environment Agency, 2013). The Environment Agency state that 75% of sites they regulate are now closed to further waste input (Environment Agency, 2013).

Bogner et al. (2008) estimate that more than 105 Mt CO_2 eq. per year are recovered from landfills world-wide. Within Europe, landfills contribute 5% of total greenhouse gas emissions of 5000 Mt per year (European Environment Agency, 2009). Methane is a potent greenhouse gas having a global warming potential 21 to 33 times higher than carbon dioxide for a 100-year time frame. Globally it is estimated that methane emission from landfills and wastewater account for 90% of the greenhouse gases from these sectors and contribute to 18% to the total anthropogenic methane emissions (Bogner et al., 2008).

2.1 Landfill processes

The processes that take place in landfills are widely described in literature through laboratory, field and theoretical experimentation (Mata-Alvarez, 2003; Themelis and Ulloa, 2007; Christensen and Kjeldsen, 1995). It is generally accepted that the organic waste fraction goes through a series of phases of degradation including hydrolysis, acetogenesis, methanogenesis and oxidation (Figure 1). The first stage of hydrolysis and the oxidation stage occur under aerobic conditions at the beginning and end of a landfills life whereas the intermediary stages take place under anaerobic conditions.

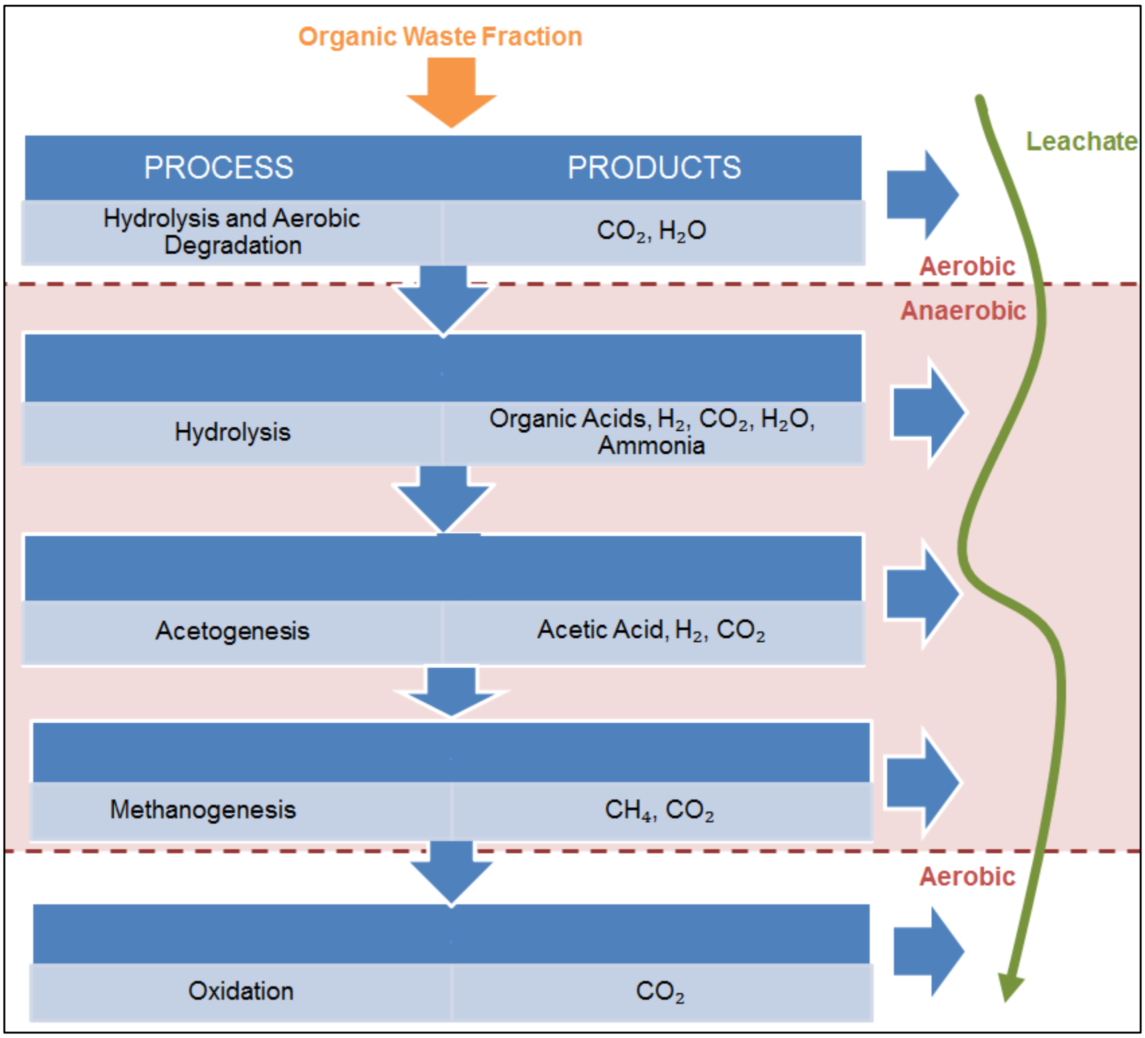

Figure 1. Organic waste fraction degradation processes in a landfill.

This evolution is facilitated by various groups of microorganisms present in the landfill at different stages which convert specific substrates to intermediary products and then gas (Figure 2). Carbohydrates, proteins and fats are first hydrolysed to sugar, amino acids and long chain fatty acids (LCFA), respectively (all are soluble organic monomers). During acidogenesis these soluble organic monomers are converted to propionic acid, butyric acid and acetic acid as well as hydrogen and carbon dioxide. Acetogenesis takes place to convert LCFA to acetic acid, hydrogen and carbon dioxide. Methane is produced during methanogenesis both from acetic acid and from hydrogen and carbon dioxide

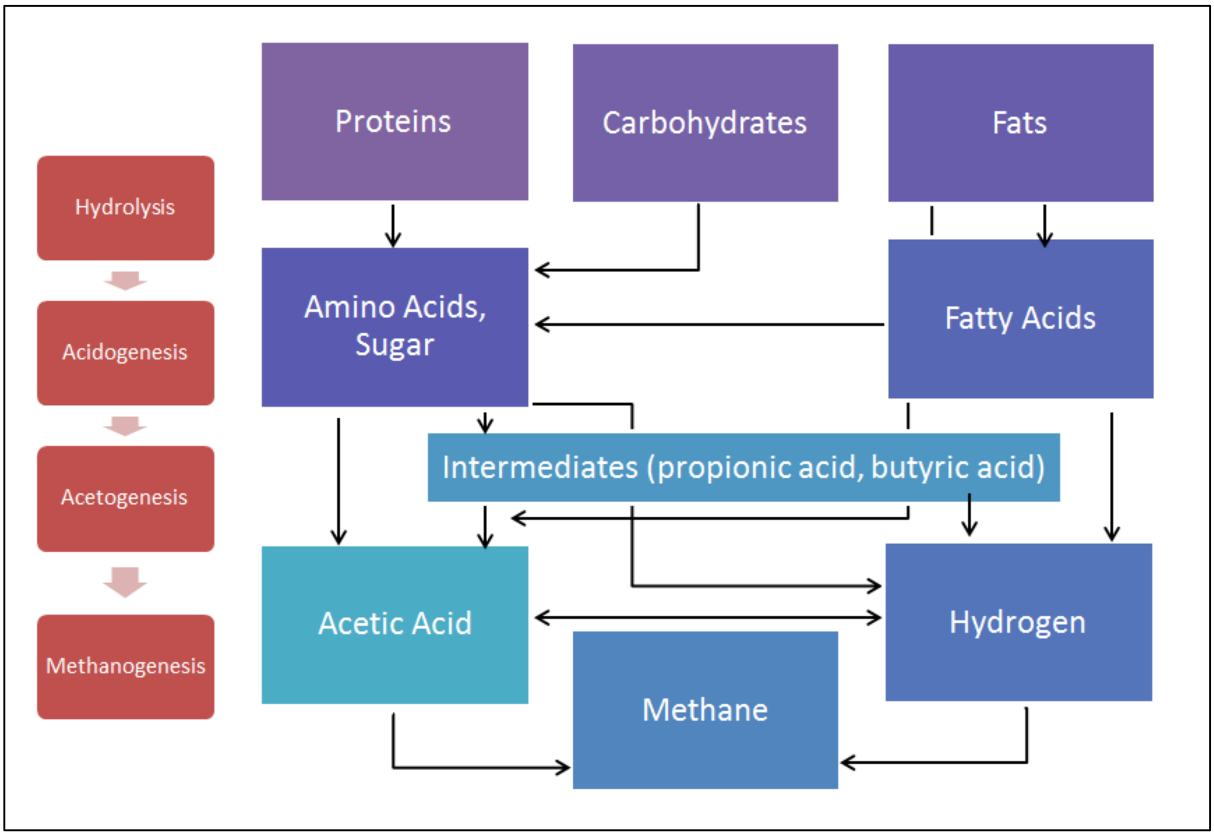

Figure 2. The degradation of proteins, carbohydrates and fats to methane.

These phases simultaneously produce variations in the environment within the landfill and produce changes in leachate, waste and gas composition (Figure 3). Leachate characteristics, or indicators, include pH, alkalinity, chemical oxygen demand (COD) and biochemical oxygen demand (BOD). The age at which a landfill site is expected to have turned to methanogenic conditions is within 2 years old and therefore the ideal range of most leachate indicators changes after this time in the DST (World Bank - ESMAP, 2004) (Table 2). For each indicator, a range of values is displayed for each stage. Due to the anaerobic nature of landfill sites, parameter values are very similar across a range of landfill sizes in Europe (Kjeldsen et al., 2002). Leachate values may not represent the entire cell and only that of the lowest section as the leachate percolates downwards through gravity. Therefore care must be taken when interpreting leachate values that the measured sample is representative of the site.

A stable landfill produces a dynamic equilibrium between all media. Kjeldsen et al. (2002) state that a strong relationship exists between leachate characteristics and the stage of landfill decomposition which is positive or negative depending on the indicator analysed.

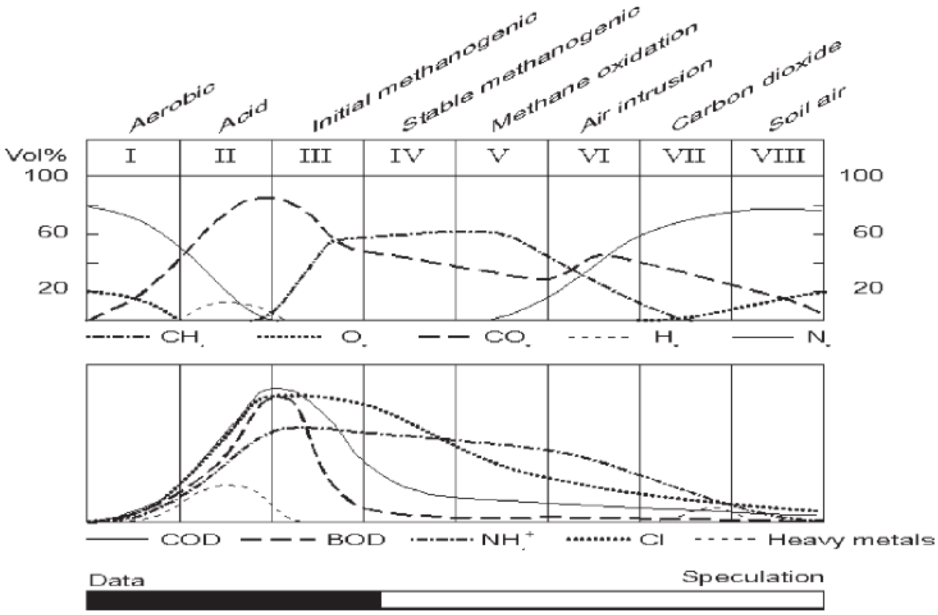

Figure 3. Landfill parameter evolution. Taken from Kjeldsen et al. (2002).

Landfill methane generation is measured as the rate of methane output in this paper. The rate of methane output in terms of cubic meters per hour provides the closest current indicator of landfill stability and landfill gas optimisation (Mata-Alvarez, 2003). What it does not reveal, however, is what may or may not be happening in the landfill.

There are many indicators of landfill methane generation and therefore many that could be used in a DST (Table 1 and Table 2). Table 1 provides guideline values for moisture content and temperature for optimal methane generation. Whilst the data is sourced from a publication in 1996, reliable data which can apply to a range of landfill sites from a more recent publication was not found. This reflects the difficulty in providing data which generalises all landfill sites and hence the need to make the user aware of the limitations of the decision support tool. Table 2 provides upper and lower boundary levels for a range of parameters in landfill leachate observed in Germany (which has the same temperate climate as the UK) from 1983 and 1988. Whilst more recent data has been published (Robinson, 2007) this only applies to very large landfill sites (5 to 10 Mm^3 of void space) and therefore cannot be used in a decision support tool for a range of sites. Hence, further work on finding the optimal ranges of the indicators of methane generation within landfill sites would improve the accuracy of the decision support tool.

Table 1. DST waste dataset tab showing moisture content and temperature boundaries for optimal methane generation (Christensen et al., 1996)

	Average	Lower	Upper
Moisture Content (%)	42.5	25	60
Temperature (°C)	30	20	40

Table 2. DST Leachate dataset tab showing typical leachate composition upper and lower boundary and average values in acetogenic and methanogenic conditions (Ehrig, 1983; Ehrig, 1988; Tchobanoglous et al., 1993). Highlighted indicators have been selected for use in the DST.

	Methanogenesis			Acetogenesis		
Indicator	**Lower**	**Average**	**Upper**	**Lower**	**Average**	**Upper**
pH	4.5	6.1	7.5	7.5	8	9
Alkalinity as $CaCO_3$	1000	5000	10,000	500	600	700
BOD5	4000	13000	40,000	20	180	550
COD	6000	22000	60,000	500	3000	4500
BOD/COD Ratio	-	0.58	-	-	0.06	-
Sulfate	70	500	1750	10	80	420
Calcium	10	1200	25,000	20	60	600

Magnesium	50	470	1150	40	180	350
Iron	20	780	2100	3	15	280
Manganese	0.3	25	65	0.03	0.7	45
Ammonia -N				50	740	2200
Chloride				150	2120	4500
Potassium					1085	
Sodium					1340	
Phosphorous					6	
Cadmium					0.005	
Chromium					0.28	
Cobalt					0.05	
Copper					0.065	
Lead					0.09	
Nickel					0.17	
Zinc	0.1	5	120	0.03	0.6	4

1. Waste composition

Waste composition reveals the potential methane output as degradable carbon content but is influenced by site specific factors (Environment Agency, 2004a). Over time, as waste is degraded, the carbon content will reduce and therefore the age of waste entering a site also influences methane output. Waste introduced to the landfill site also contains bacteria, nutrients such as nitrogen and phosphorous and moisture which are essential to bacteria growth and subsequent methane production. However, complete waste composition data is often not available at landfill sites and is therefore not used as an indicator in this DST.

2. BOD/COD ratio

The BOD/COD ratio records the reduction in biodegradable matter in a landfill. A relatively high ratio can be expected at the initial stages of a landfill life as the organic waste fraction is still available to be degraded (Table 2). This will decrease towards zero over time as the waste is degraded and becomes inert. A low BOD/COD ratio indicates a low level of volatile fatty acids (VFAs) and relatively higher levels of humic and fulvic-like compounds as VFAs are consumed as quickly as they are produced in later, stable, stages of a landfills life (Kjeldsen et al., 2002). The BOD/COD ratio is a necessary but insufficient indicator of landfill methane generation as it does not take into consideration factors such as the variation in waste content throughout the site (Barlaz et al., 2002). Therefore, further indicators mentioned below are also needed to ensure a wider view of landfill methane generation.

3. Moisture Content

Kjeldsen et al. (2002) state that moisture content is the single most important parameter for gas production. Moisture content above between 25-60% increases biogas production for several reasons including transporting substrates, microbes and nutrients and diluting toxic substances (Table 1). However, saturation of a landfill above a 60% moisture content causes a drop or cessation of gas production as the microbes can no longer perform the conversions.

4. Leachate

Leachate is excess moisture in the landfill including the dissolution of soluble materials, the quality of which is a function of decomposition processes and other processes (Figure 4). This figure displays how leachate enters and exits a landfill site through rainfall and waste addition to leachate extraction and seepage through the liner.

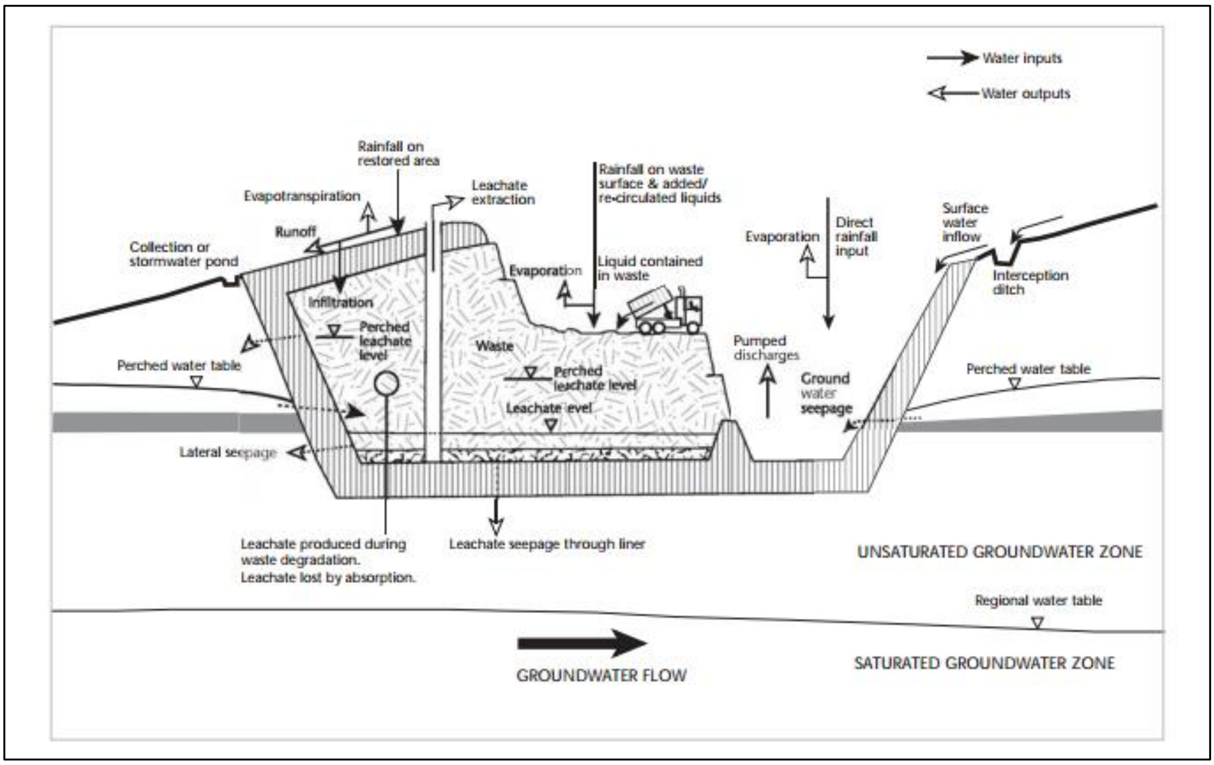

Figure 4. Landfill water balance including rainfall input and leachate output pathways. Taken from (Environment Agency, 2003).

Leachate values reveal the environmental conditions in the landfill but may not be representative of one point in time or the whole area of landfill (Barlaz et al., 2002). This is due to leachate only representing the deepest section of the landfill which will be more decomposed than at the top (Kjeldsen et al., 2002). Also, the hydraulic retention times varies widely between landfills and therefore leachate results may relate to different time periods across the site. The hydraulic conductivity (how easily leachate can pass through a landfill site) varies at different depths of a landfill which therefore influences the rate at which leachate should be re-introduced to the landfill site for re-circulation (Figure 5). The graph shows that much higher infiltration rates can be achieved when hydraulic conductivity varies over the site but the authors highlight that the rates are dependent on how compact the waste in place is assumed to be.

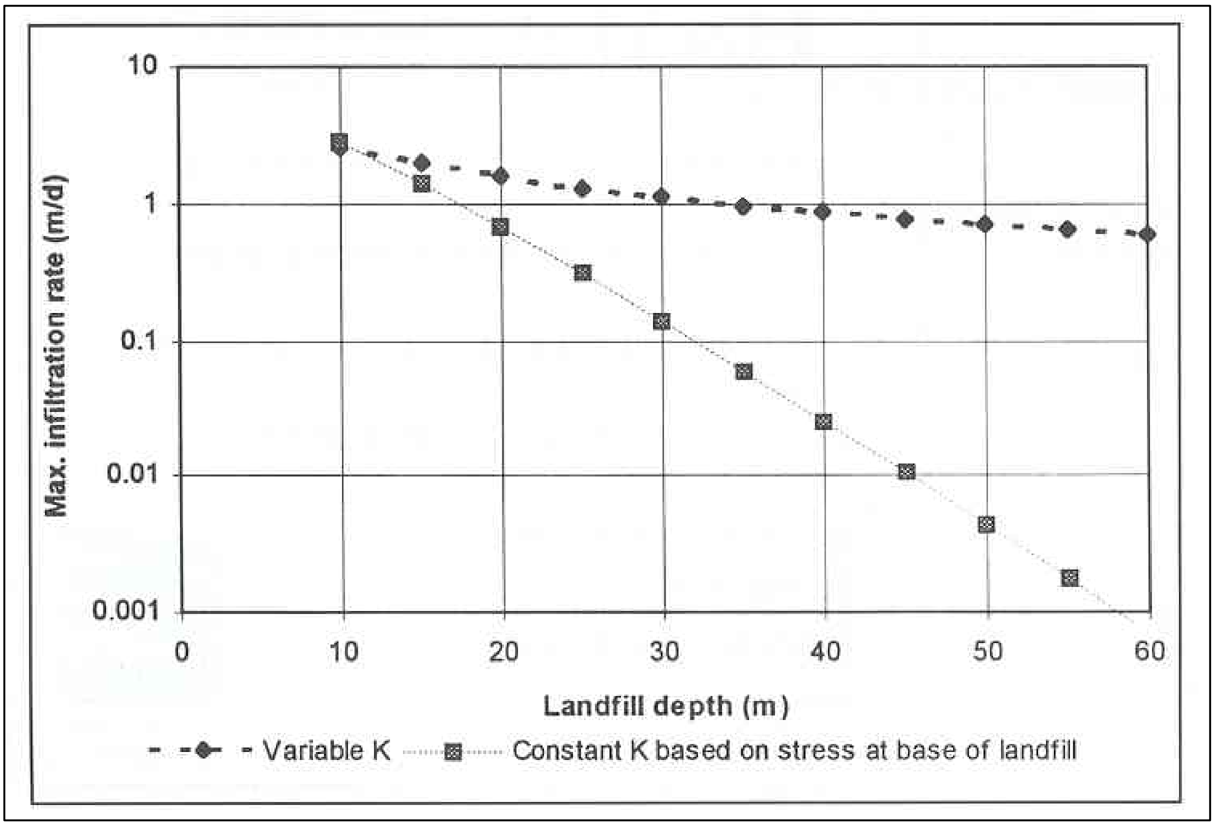

Figure 5. The effect of landfill depth on the hydraulic conductivity of landfill waste (K) and hence maximum infiltration rates. Taken from (Powrie and Beaven, 1998).

Leachate facilitates the pH and alkalinity of a landfill which are both essential to microbial growth and activity and buffering the increasing amount of acidic products in the early stages of the waste decomposition (Mata-Alvarez, 2003).

5. pH

pH is a measurement of the hydrogen ion concentration and indicates acidity (Mata-Alvarez, 2003). pH is described as a poor stand-alone indicator but does indicate the stage of waste degradation in a landfill site as the pH will be lowered by the production of LCFA.

6. Alkalinity

Alkalinity is the measurement of the ability of leachate to buffer sudden changes in acidity. It measures process stability more quickly than pH and is therefore assigned a higher weighting than pH in the weighting calculation (Mata-Alvarez, 2003).

7. Temperature

Heat is inherently generated within landfill sites during the conversion of waste to gases. Higher temperatures within a range of 20-40°C increase methane production (Christensen et al., 1996). Ambient temperatures outside a landfill site can also increase the temperature within a site but this reduces with lower depths of waste landfilled.

8. Inhibitors

Other parameters include the presence of heavy metals, sulphates and ammonia which, in high levels, are known inhibitors to methanogenesis (Chen et al., 2008).

Completion of landfill degradation processes is made complex by the limited accessibility within a closed landfill site, the lack of knowledge in what is contained in each cell and the number of parameters involved in monitoring landfill stability. Also, there is no a single parameter that can be altered without affecting the others. The most recognised method of completion is leachate recirculation which adds moisture content evenly and consistently throughout the landfill (Mali Sandip et al., 2012) which increases the moisture content from 15-20% to 40-50% (wet weight) and facilitates the transportation of nutrients, substrates and microorganisms (Kjeldsen et al., 2002). The leachate can also be added with a buffer solution to combat acidic effects of acetogenesis to restore the balance for methanogenic bacteria. The application of leachate recirculation to landfill sites with pH buffering to leachate injections in field-scale studies has shown to increase biogas production (Reinhart et al., 2002). However, the author is not aware of field-scale studies describing the precise methodology used. Other less practiced and research methods include the pre-shredding of waste to ensure an even distribution of landfill components and pre-closure aeration. Aeration allows for some aerobic degradation of the waste which results in the avoidance of an acidic stage but the release of potential methane resources which would otherwise be captured by the extraction system.

2.2 Landfill gas models

Landfill gas (LFG) emissions are routinely calculated but not always measured directly. The decomposition of waste in landfills and the resultant methane and landfill gas emissions are predicted with the help of models which summarise the very complex chemical and biological reactions involved. Several models of varying levels of complexity with different orders of kinetics have been developed, namely zero-order, first-order and second order models as well as some more complex models (Kamalan et al., 2011). Landfill gas prediction is currently known as unreliable and inaccurate due to wide variance in results between different models and between prediction and actual results (Scharff and Jacobs, 2006). While the inaccuracies are highlighted and calculated, these models are an essential tool for landfill operators as well as for wider national emission reporting, as there is no other way of predicting methane emissions. Oonk (2010) estimates the error of landfill gas models to be 30% (either side of the predicted value) due mainly to estimations in waste methane yield. The prediction of emissions can be used in a DST to measure the difference between expected and actual values. Landfill gas prediction is important both to address environmental issues of greenhouse gas emission and to predict future income from the sale of energy from landfill gas by operators.

The most popular models have been the first order models and overviews and formulae for the most used first order models (GasSim, LandGEM, TNO, Afvalzorg and EPTR) are presented by Kalaman et al. (2011) and Thompson et al. (2009). There are a variety of factors influencing the generation of LFG and methane. The three key factors for methane generation models for a landfill site are (Thompson et al., 2009):

1. the amount of waste disposed since commissioning
2. the degradable organic fraction
3. the decay rate (of each fraction and as a whole).

As many old landfills (pre-2005) do not hold records of waste quality or quantity the composition of the waste is not always known, and therefore estimations and extrapolations are necessary in many cases. More recently, the IPCC guidelines

(2006) establish a method that can be applied to all countries/regions and provide default values (e.g. regional generation rates), estimates and calculation methods to overcome lack of historical data (IPCC, 2006). However these estimates introduced higher uncertainty in the final results and sites with poor management data have the highest uncertainties in their calculations. Uncertainties have been traced back to the lack of data with regards to the amount and composition of the waste, but also to assumptions that have to be used such as decomposition rates, methane generation rates, oxidation rate and capturing efficiency among others. In addition, the overall rate of LFG emission can be influenced by operational interventions like waste compaction, leachate recirculation or aerobic landfilling and theoretically these factors should also be taken into consideration when modelling generation.

The main criticism of methane prediction models is their lack of accuracy and validation (Thompson et al., 2009; Bogner and Matthews, 2003). Therefore, simple models are preferred (Oonk, 2010). Additional factors contributing to the inaccuracy of models include the percentage of landfill gas lost to the atmosphere and the percentage methane content. Models such as GasSim and LandGEM assume 50% of landfill gas is methane but this has been proven to vary widely on landfill sites (US EPA, 2005; Golder Associates, 2013). Each model is limited by the assumptions made. A major assumption is that there is a direct relationship between carbon degradation and biogas output even though it is known that inhibition plays an important role. Improvements may be made to the models in the use of more accurate kinetic values and the inclusion of other substrates including proteins and lipids.

This clearly highlights why methane generation models need to be validated (i.e. predicted methane has to be compared with methane recovery data). One of the more accurate methods to validate methane prediction models at landfill sites is the carbon balance approach (Spokas et al., 2006).This approach takes into account that methane generated can be oxidized recovered and stored within the landfill site. It can also migrate and only the remaining amounts are emitted into the atmosphere. Each component of the carbon balance can be quantified, modelled, optimised and engineered to reduce the amounts of amounts of methane emitted and maximise LFG collection.

Methane potential (L_0) is an important parameter in most models which is defined as the total methane produced by waste over its lifetime. This can be calculated by finding the amount of waste (W) and the concentration of organic carbon (DOC) (Equation (2-1)). The DOC is calculated from the fractionation of waste e.g. percentage garden waste, food waste. However, a proportion of organic carbon is non-degradable and needs to be accounted for by the factor DOC_f. DOC_f is a constant between 0.4 and 0.7 in most models. Methane potential is thus calculated as:

$$L_0 = 1.33 \times W \times DOC \times DOC_f \qquad \textbf{(2-1)}$$

The methane potential is then used in a given function to predict its release over time. The time taken for its release is determined by the half-life, or k-value. The lower the half-life or higher the k-value, the shorter time it takes for methane to be released. A first order decay model, as used by the US EPA in their LandGEM model assumes that the majority of gas will be emitted immediately and with gradually decline over time (US EPA, 2005) (Equation (2-2)). However, in reality, landfill gas production has a lag time after the landfill is covered and closed which is not included in the model. The time taken to produce landfill gas varies from months to years and is dependent on a wide range of factors including climate and waste quality (Gregory et al., 2003; IPCC, 2006; Robinson, 2007). Models can incorporate this by assuming a zero gas production for a given period of time at the start. Another problem with these models is that they assume that gas production is uniform throughout a landfill waste mass when in reality some areas may have access to oxygen, be saturated with leachate or subject to toxic conditions which would reduce gas production. Therefore a methane correction factor can be used to adjust for this (Oonk, 2010).

$$G = WL_0ke^{-kt} \qquad \textbf{(2-2)}$$

G Methane production rate (m^3/yr)

W Annual waste acceptance rate (tonnes/yr)

Lo Ultimate methane yield m^3/tonne

k Decay rate constant

Table 3. A comparison of methane potential and half-life values used in landfill gas models for MSW (adapted from Oonk (2010).

Model	L_0 (kg/ton)	Half Life (Yr)
IPCC	63	12-23 (slow)
		7 (moderate)
		4 (fast)
GasSim	51	15 (slow)
		9 (moderate)
		6 (fast)
LandGEM	122 (CAA)	14 (conventional)
	72 (inventory)	35 (arid)
E-PRTR (France)	55	5-10.

As waste is generally added to landfill over a number of years, multiple equations are used to sum the methane emissions from each section of waste. This model is criticised as it produces a discrete value each year, rather than the continuous amount observed (Oonk, 2010). This means that landfill gas emissions are underestimated. LandGEM has been updated to address this issue by calculation methane emissions for every tenth of the year to increase the landfill gas estimate (Reinhart et al., 2005) (Equation (2-3)).

$$G = (W/10)L_0 ke^{-kt} \qquad \textbf{(2-3)}$$

Multi-phase models specify degradation k values for different waste types, such as food waste degrading faster than newspaper. This approach assumes that waste types do not affect each other (are independent) in landfill degradation unlike the simplified first order decay model above. Higher quality and quantities of data are necessary for this type of model which is typically unavailable to landfill operators (Oonk, 2010). These points limit the accuracy of this approach over a simpler version. Four models with a wide presence in literature are presented below.

2.2.1 IPCC model

The IPCC model (IPCC, 2006) was developed to allow nations to report methane emissions from all landfill sites. It is a transparent model which requires the input of total waste mass and waste composition by source or category (food waste, garden waste etc.). The model has the option to use the first order decay or multiphase equation. The climate conditions are selected for each nation which alters the k-value used.

2.2.2 E-PRTR (France)

This model was developed in France and uses very simplified methane generation values for each tonne of waste in a fill-in table to predict landfill gas output (Ademe, 2003) (Table 4).

Table 4. E-PRTR (France) landfill gas model (Ademe, 2003). For biodegradable waste, these values are halved.

Year period considered (year)	Methane produced per tonne (m^3/tonne)
1 - 5	6.6
6 - 10	3.4
11 - 20	1.8
21 - 30	0.8

2.2.3 GasSim

GasSim (Golder Associates, 2013) was commissioned by the Environment Agency and was developed within the programme GoldSim. It is based on UK waste statistics both observed and predicted for time periods such as 1980-2000. A variety of environmental issues are addressed from methane emissions to local air quality. The tool does not allow insight into its inner equations but the theory is described in the manual. GasSim uses a multi-phase first order decay equation to calculate landfill gas production (Equation (2-4) and Equation (2-5)) but does not take into account protein and lipid carbon content (9% of total carbon) (Barlaz et al., 1989). The ability of the user to input waste mass in waste categories and input additional data such as moisture content makes it, along with the IPCC model scientifically robust.

$$C_t = C_0 - (C_{0,1}e^{(-k_1 t)} + C_{0,2}e^{(-k_2 t)} + C_{0,3}e^{(-k_3 t)}) \quad \textbf{(2-4)}$$

$$C_x = C_t - C_{t-1} \quad \textbf{(2-5)}$$

Where:

C_t Mass of degradable carbon up to time t (tonnes)

C_0 Mass of degradable carbon at time t = 0 (tonnes)

$C_{0,i}$ mass of degradable carbon at time t = 0 in each fraction (1, 2, 3 i.e. rapid, moderately and slowly degradable fractions) (tonnes)

C_x mass of carbon degraded in year t (tonnes)

t time between waste emplacement and LFG generation (years)
k_i degradation constant for each fraction of degradable carbon (per year)

K values rapid 0.076-0.694; moderate 0.046-0.116; slow 0.013-0.076 for moisture levels less than 30% to greater than 60% (Gregory et al., 1999).

2.2.4 LandGEM

The USEPA developed the Landfill gas emissions model (LandGEM) which uses a first order decay model in an excel spreadsheet to predict landfill gas emissions (USEPA, 2013). Various parameters can be chosen such as the k-value and the methane potential. The model is limited by its assumption that all waste degrades at the same rate, unlike other models mentioned above which allow the user to define waste mass in categories. As LandGEM has a uses half-lives much higher than the other models, methane prediction will also be higher even though higher methane potential values are also used. Oonk (2010) therefore questions the scientific reliability of the model.

2.3 Landfill methane generation decision support tool

There is currently no decision support tool used in literature specifically for the assessment of landfill performance. The majority of tools focus on long-term environmental risk management objectives in accordance with environmental regulations. However, landfill performance is also important for landfill operators to assess in the short term in order to achieve additional goals such as faster landfill gas generation and optimisation of methane collection rate. Within the field of environmental science, however, decision support tools are widespread in areas as diverse as sustainability and contaminated land management (Krajnc and Glavič, 2005b; Sorvari and Seppälä, 2010).

A decision support tools are “documents or software produced with the aim of supporting decision making i.e., something that carries out a process in decision making” (Bardos et al., 2002).They provide a robust, consistent, transparent and reproducible method for the decision making process (Sorvari and Seppälä, 2010). In order to decide which method to use in the landfill methane decision support tool an assessment of methods currently used to produce environmental DSTs is provided.

There are three different methods used in landfill decision support tools, target value approaches, impact/risk assessment and performance based systems (Laner et al., 2012). The current methods focus on helping the decision makers to consistently and transparently identify and reduce risks involved in landfill aftercare management such as groundwater pollution. There is no world-wide or European consensus on the assessment of landfill sites in terms of method or enforcement. Currently in England and Wales, a combined environmental risk and impact assessment is used by the Environment Agency. In this system, compliance with set standards can result in a landfill operator no longer needing to provide aftercare management (Environment Agency, 2010). Hydrogeological risk assessment must also be carried out by the operator to prove that pollutant concentrations will not have an unacceptable impact on groundwater (Environment Agency, 2010). The criteria for landfill gas are set at target levels of 1.5% methane of total landfill gas and 5% carbon dioxide continually for a minimum of 2 years. Landfill gas criteria are also deemed to be met if methane and carbon dioxide levels are similar to background levels or landfill gas flow rate is less than 0.015 m^3 per hour for methane and 0.022 m^3 per hour of carbon dioxide continuously over a 2-year period as well. The site must not have observed any topographical changes to ensure site settlement and stability.

2.3.1 Target value approach

The target value approach defines values which must be met for various parameters to terminate post closure monitoring (Table 5). This approach is criticised for its lack of site specific evaluation which could lead to over-management of a site as well as industry wide problems of representative waste sampling and unreliability of biodegradability tests (Laner et al., 2012). Stegmann et al. (2006) provide values for landfill gas, leachate, waste composition and settlement and consider aftercare no longer necessary when landfill processes have been completed and are not likely to be reactivated. However, meeting these values would require aftercare for extensive periods and is therefore not realistic (Laner et al., 2012). The authors therefore suggest that a site specific basis is needed which lacks definite targets.

Table 5. Criteria for end of landfill aftercare period, reproduced from Laner et al. (2012).

	Stegmann et al. (2006)	Cossu et al. (2007) and Pivato (2004)	Knox et al. (2005)
Leachate	COD: 5–20 g/m^2year	COD: <200 mg/l	NH_4–N: ⩽10 mg/l
	NH_4–N: 2.5–10 g/m^2 year	BOD_5/COD ratio: <0.01	
	Cl: 10–20 g/m^2 year	NH_4: <300 mg/l	
	AOX: 0.01–0.05 g/m^2 year (emissions to subsurface)		
Landfill gas	Methane production rate: <25 m^3 CH_4/h and <0.0005 m^3 CH_4/m^2 h	Gas generation rate: <25 m^3/h	Landfill gas emission rate: ⩽0.0084 m^3/(m^2 h)
		Area-specific methane generation rate: <0.001 m^3CH_4/(m^2 h)	
Waste	TOC: ⩽150 mg/l	Biodegradability: respiratory index (RI_4): ⩽2.5 mg O_2/g DM	Biochemical methane potential (BMP): ⩽0.0002 m^3CH_4/kg DM
	NH_4–N ⩽50 mg/l	Methane generation potential in 21 days: 0.01 m^3CH_4/kg DM	Cellulose/lignin ratio (corrected for plastics): <0.2
	AOX ⩽0.5 mg/l (additionally: heavy metals, organic compounds, pH, and elec. cond.)		
	Biodegradability: Respiratory index (RI_4): ⩽2.5 mg O_2/g dry matter (DM)		
	Methane generation potential in 21 days: 0.01 m^3CH_4/kg DM		

AOX: Adsorbable organically bound halogens; DM: dry matter; elec. cond.: electric conductivity.

Cossu et al. (2007) also use a target value approach to assess the “final storage quality” for a landfill site. Final storage quality is not well defined in literature but should meet Landfill Directive Waste Acceptance Criteria (CEC, 2003) for inert waste (Valencia et al., 2009). This means that waste should have the same properties as the environment in which it is surrounded and not cause short or long term pollution (Baccini, 1989). However the term is disputed as being inappropriately generic for an inherently site-specific state (Laner et al., 2012). Set values for landfill gas, leachate and waste parameters are identified in order to obtain this status. A site specific risk assessment can then take place to identify environmental risks. Knox et al. (2005) also addresses the issue of defining target values for final storage quality as a part of the Brogborough landfill test cell project. Target values are highlighted for landfill gas and leachate emissions as well as for MSW residual biodegradation. A range of 95-99% removal of degradable organics is suggested based on a literature review and industry regulations but there is currently a lack of consensus on which biodegradability method to use which limits the ability to compare different landfills to the same criteria value (Wagland et al., 2009; Laner et al., 2012). All target value approaches acknowledge that current test methods are inadequate to highlight landfill performance and that therefore a site-specific approach must be undertaken based on documented landfill cases.

2.3.2 Impact/risk assessment to evaluate aftercare

Scharff et al. (2007) develop a risk assessment approach using landfill aftercare criteria to find an acceptable level of risk and state that due to local conditions, criteria must be site specific. Using the source-pathway-receptor model, the risks of landfills need to be assessed and the likelihood of their occurrence (European Commission, 2003). Scharff et al. (2011) continuing with this work, use geochemical modelling combined with threshold leachate contamination values as criteria for aftercare in a pilot study. The authors state that a purely target value based approach does not encapsulate issues of local conditions variance and that a risk based approach is necessary. Hall et al. (2007) similarly focus on landfill leachate as the primary risk and model leachate migration and develop threshold values within LandSim (Environment Agency, 2004b). The model's aim is to calculate the time period required to achieve "equilibrium status" which is defined as when the level of emissions is such that the environment is able to perform natural attenuation to prevent environmental harm and no further management is therefore required (Hall et al., 2007). However no criteria for the completion of aftercare are proposed. Laner et al. (2012) question the viability of risk based approaches due to the uncertainty involved in risk assessment and the reliance on groundwater models based on wide sweeping assumptions.

2.3.3 Performance based systems

Performance based systems combine target value and risk based approaches to help the operator to meet compliance objectives and reduce the need for management over time. The evaluation of post closure care (EPCC) methodology aims to protect the environment by site-specifically monitoring landfill leachate, gas and groundwater aftercare management (Morris and Barlaz, 2011). Aftercare strategies are proposed according to the results of the analysis. The overall objective and end use of the landfill needs to be taken into account from the start of the tool. Changes in management are monitored by the operator to make sure no adverse effect has taken place. There are also threshold values which demand a given response.

The method is commended for its transparent assistance in aftercare management but criticised for its reliance on monitoring current emission levels. Laner et al. (2012) criticised the lack of strategy to reduce, for example landfill gas emissions. Sizirici et al. (2011) have developed an alternative performance based approach which produces a landfill score bases on the ranking of various factors. An expert is asked to assign a value of 1-10 on factors such as leachate management and operational factors and the scores are weighted and aggregated to give a critical, acceptable or good score. A critical condition represents a potential threat to human health and the environment (HHE) and management needs to be undertaken. Acceptable scores indicate the continuation of current management practices and good the gradual decline of practices (Sizirici et al., 2011).

2.4 Multi criteria analysis

Multi criteria analysis (MCA) (or multi criteria decision analysis) is essential for the use of a decision support tool in a landfill situation due to the wide range of processes and parameters involved. The analysis has the ability to combine information associated with each option by setting universal criteria including costs, benefits and stakeholder opinion in order to assess the most preferred option (Huang et al., 2011). It is a widely used method in modern policy decision making in order to identify the most preferred option, to highlight the presence of options or to rank options (Dodgson et al., 2009). Large aspects of the analysis are decided by the decision makers including the selection of options and criteria, weighting and performance scores which has positive benefits including the ability to produce a situation specific tool and the application of professional knowledge. The technique implicitly requires these decisions to be highlighted and replicated. However, flaws in the technique emerge with the introduction of systematic bias from the decision maker and the inability to encompass different viewpoints (Dodgson et al., 2009). Scores for each option based on the set out criteria are normalized in order to compare them across different units and are presented in a performance matrix. Dodgson et al. (2009) highlight that criteria and options need to be finite and as few as is reasonably possible in order to limit the data gathering and processing necessary. Different methods of MCA are discussed below to assess which are suitable for a landfill methane decision support tool.

There are many different methods of MCA but all are based on the data gathered in the performance matrix. Methods include multi attribute utility theory and a linear additive model. The analytical hierarchical procedure is the most common in environmental science literature MCA accounting for half of 312 papers studied (Huang et al., 2011). The authors relate this dominance to the method's availability of expertise and software comparative to other techniques. A direct analysis of the performance matrix can be performed whereby professional knowledge is used to view the option which outcompetes all others, if possible. However, this lacks reproducibility and scientific basis. Dodgson et al. (2009) states the following criteria necessary for the selection of an appropriate MCA method:

1. Internal consistency and logical soundness
2. Transparency
3. Ease of use

4. Data requirements not inconsistent with the importance of the issue being considered
5. Realistic time and manpower resource requirements for the analysis process
6. Ability to provide an audit trail, and
7. Software availability, where needed.

Multi attribute utility (or value) theory uses a mathematical function to maximise the decision maker's utility (Keeney and Raiffa, 1976). The method is based on the theory that the decision maker attempts to maximise its utility for each criteria. Criteria are not weighted but are given a scaling constant. The researcher needs to ascertain the preference function through a series of questions including the highest and lowest value of each criteria and ask what least amount of 'x' would you accept for certain instead of taking a given gamble (Cho, 2003). Problems include the subjectivity of gambling situations and difficulty in perceiving the relative values for each criterion. It is a complex method which allows for the incorporation of uncertainty and attributes are not mutually independent (Dodgson et al., 2009). Therefore, this method is more suited to complex projects with a high budget. Multi attribute value theory incorporates weightings but only on an interval scale *e.g.* assigning values from 0-100 for each criterion.

Most MCA methods use a linear additive model which provides mathematically sounds and producible support for decision makers (Dodgson et al., 2009). The Measuring Attractiveness by a Categorical Based Evaluation (MACBETH) and the Ratio Estimation in Magnitude or deci-Bells to Rate Alternatives which are Non-Dominated (REMBRANDT) techniques use this method (Bana e Costa et al., 1999; Lootsma, 1992). The analytical hierarchical process (AHP) uses a linear additive model which gives a value score for an option for each criterion, multiplies this by the weight of the criteria and sums the scores together (Saaty, 1987). The AHP varies from other linear additive models by using pairwise comparison of criteria to assign weights (Saaty, 1987; Vaidya and Kumar, 2006). A pair wise decision is made between each parameter on a scale of 1 to 9 where 1 indicates that two parameters are equivalent in their indication of objective and

9 that one parameter is 9 times more important than another one (Contreras et al., 2008). A hierarchy of parameters is therefore built which can then be aggregated to weight each parameter. This technique is widely used in MCA processes (Contreras et al., 2008). Similar positives and negatives of this technique occur as with MCA such as the ability to apply situation specific professional knowledge but with the bias involved in allowing the decision maker to decide which parameter is more important than others. The AHP provides a method which is easily understandable and simple to use but its theoretical basis has been criticised for example that rank reversal of two independent options can occur when a new option is introduced (Belton and Gear, 1983). However, this has been improved in recent analytical hierarchical process models such as REMBRANDT (Olson et al., 1995; Lootsma, 1999).

The outranking technique, such as ELECTRE I, differs from those previously mentioned in that options are eliminated if they score badly on a criterion (Roy and Mousseau, 1996). However, weighting of criteria is taken into account. Criticisms lies with the threshold values for an option to be defined as outranked being largely subjective (Dodgson et al., 2009). The method is less commonly used in the UK and USA.

2.5 Summary

The literature review has highlighted the need for a DST that helps the user to understand complex landfill processes. This can be achieved by developing a mathematically transparent model which incorporates both aggregate performance scores and provides a breakdown of landfill gas indicators. The MCA technique used by Krajnc and Glavic (2005) is chosen for use in the decision support tool which enables the aggregation of a wide range of landfill gas parameters and the AHP allows for the easy understanding of how weightings for each indicator are derived.

3. A DST for landfill methane generation

3.1 Interface

The tool was developed in the well-known Microsoft Excel 2010 software in order for it to be easy to use and accessible to the widest range of audience. The tool is available in Appendix B. The tool is made up of a series of worksheets for the user to input data, to display results, remedies to landfill gas problems, calculations and underlying data. The user is able, at a basic level, to enter data for a specific site, view results and remedies. At a more advanced level further tabs are available to understand how the scores are calculated and certain model parameters can be altered. A manual is provided to assist the user in the use of the tool (Appendix C).

3.2 Method for calculating the landfill site scores

As a quantitative method, the target value approach was chosen to meet the aim and objectives of the landfill methane generation decision support tool. However, the literature review highlights the need for the tool user to be aware of the limitations of using a target-value approach including the need to recognise site-specific issues at landfill sites.

The landfill methane generation is assessed by two scores (Figure 6). A green, yellow and red traffic light system is used to indicate good, average and poor scores. The first score assesses the actual methane output rate for each site against what rate is predicted for that site using the United States Environment Protection Agency (USEPA) landfill gas model, LandGEM (US EPA, 2005). The LandGEM model was chosen as it requires a small amount of data input but provides an estimation of the evolution of cumulative landfill gas emissions over time. This provides benefits over simpler models such as E-PRTR model (Ademe, 2003) which only provides a total value of gas emissions which cannot be used in a decision support tool to assess methane generation at yearly intervals.

The second score assesses the landfill environment by using the MCA method used by Krajnc and Glaviĉ (2005b; 2005a) to score each landfill gas indicator against the ideal range for that indicator for methane generation. In this way, the methane output score is the primary source of assessment for each landfill site and the landfill gas indicator score provides a secondary insight into why a landfill may have good, average or poor methane generation. Each indicator is given a score which, if red, suggests that it is negatively influencing methane generation.

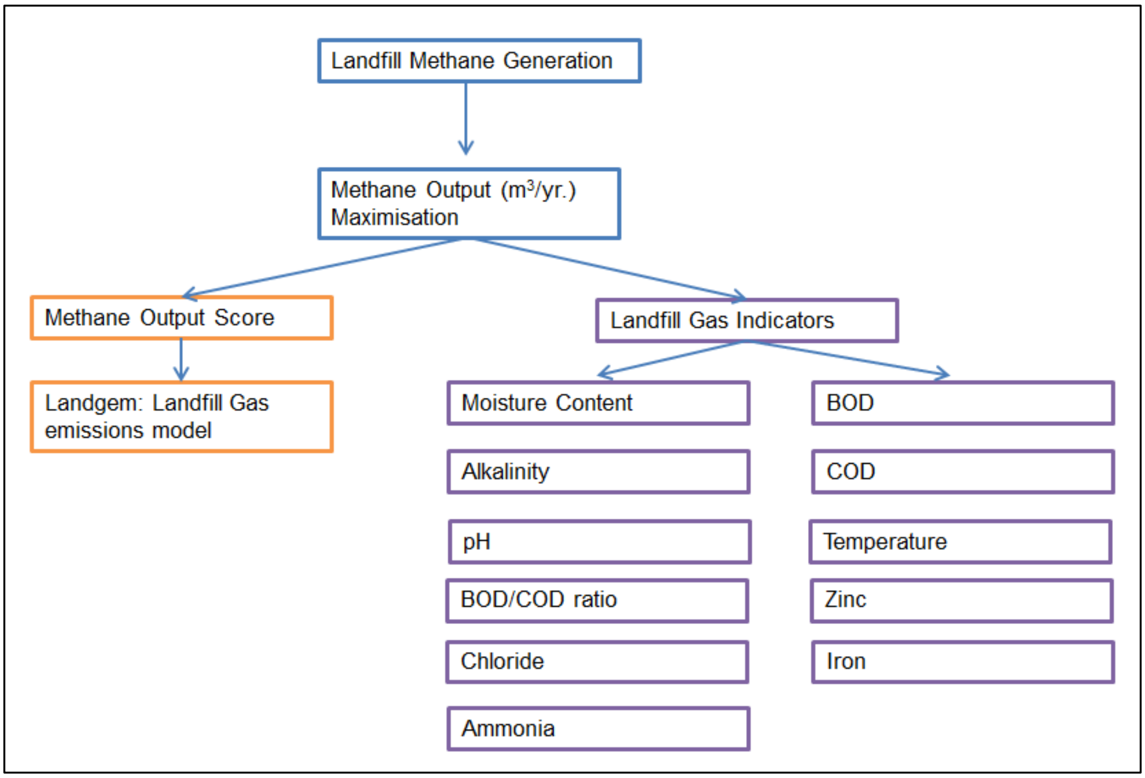

Figure 6. The landfill methane generation DST is made up of the methane output score and the landfill gas indicators score.

3.2.1 Methane Output Score

$$M_{x,t} = \frac{B_A - B_I}{B_I}$$

The methane output score is calculated by comparing the predicted methane output rate to the actual methane output rate for a given site. The methane output is predicted using the LandGEM model (Equation (3-1)). The score is expressed as the percentage deviation from the predicted value. Therefore, a score of 0% represents the actual methane output being equivalent to predicted output.

$$M_{x,t} = \frac{B_A - B_I}{B_I} \tag{3-1}$$

Where M is the methane output score for site 'x' at time 't', 'B_A' the actual methane output (m^3/yr) and 'B_I' the ideal value for methane output (m^3/yr).

The methane output score is given a red, yellow or green traffic light to highlight good, average or poor methane output rate (Table 6). A green traffic light indicates a score higher than 30% which is determined by defining the error margin of the LandGEM model to be 30% either side of the actual score (Oonk, 2010). A yellow traffic light represents a score of -30-30% whilst a red traffic light represents a score below -30%. The boundaries over which red, yellow and green traffic lights are given can be changed in further versions of the model.

Table 6. A description of the traffic light system boundaries for the methane output score.

Traffic Light	Score Boundary (% deviation from LandGEM prediction)	Description
Green	Greater than >30%	Good performance - methane output is currently higher than predicted levels, no action necessary.
Yellow	Between -30% and 30%	Average performance - methane output is currently at predicted levels (within a model error margin of 30%) and close monitoring of red and yellow landfill gas indicators is necessary.
Red	Less than -30%	Poor performance - methane output is currently well below predicted levels, remedial action is necessary for red and yellow landfill gas indicators.

3.2.2 Methane output prediction

The landfill gas model "LandGEM" is used to predict LFG production or potential methane generation capacity for up to five sites (US EPA, 2005). The methane calculation worksheet is used from the original LandGEM model. The calculation feeds from the user input age, waste acceptance and potential methane generation capacity (L_0). The default parameters for a conventional landfill (inventory) are used:

Decay rate constant: $k = 0.04$

Potential methane generation capacity: L_0 = 100 m^3/Mg

However, LandGEM assumes all waste accepted into the landfill site is MSW which is not necessarily the case. Therefore the potential methane generation capacity value can be altered by the user depending on the composition of waste if known.

The decay rate constant (k=0.04) is set in the DST however the potential methane generation capacity can be changed by the user. A default value of 100 m^3/ Mg is provided if the value is unknown. If the L_0 value is known, the user can enter this value into the user input tab. A waste composition with a higher cellulose content has a higher L_0 value and therefore produces a higher methane output. A guide is provided as background for a range of L_0 values used in the LandGEM model based on wet bioreactor, conventional landfills and CAA regulatory values.

3.2.3 Landfill gas indicator score - multi-criteria decision analysis

The second element of the DST is to calculate a score for the landfill gas indicators (Figure 6). A multi-criteria decision technique is used to combine the scores of the landfill gas indicators. In order to achieve the aim of an understandable tool, the method used by (Krajnc and Glavič, 2005a; Krajnc and Glavič, 2005b) was followed (Figure 7). This method provides a mathematically transparent composite index score by combining key measurable leachate, waste and biogas parameters and comparing those to ideal values. The parameters are assumed to be independent as no field-scale data was available to conduct sensitivity analysis on. The scenario testing performed in this paper did not provide enough data to provide statistical significance for a Spearman's rank correlation test. Also, the literature review did not highlight a sensitivity analysis to quantify the effect of one parameter on another. Meima et al. (2008) found that water content had the greatest influence on the environmental conditions for microbial growth including temperature and pH but did not quantify what this effect was. Other parameters that are dependent on each other are pH and heavy metals in which the solubility of heavy metals into landfill leachate increases in acidic conditions (Kjeldsen et al., 2002). However, the effect of inhibitors to methane generation such as methane generation can be controlled by the control of the more influential parameters of moisture content, alkalinity and pH.

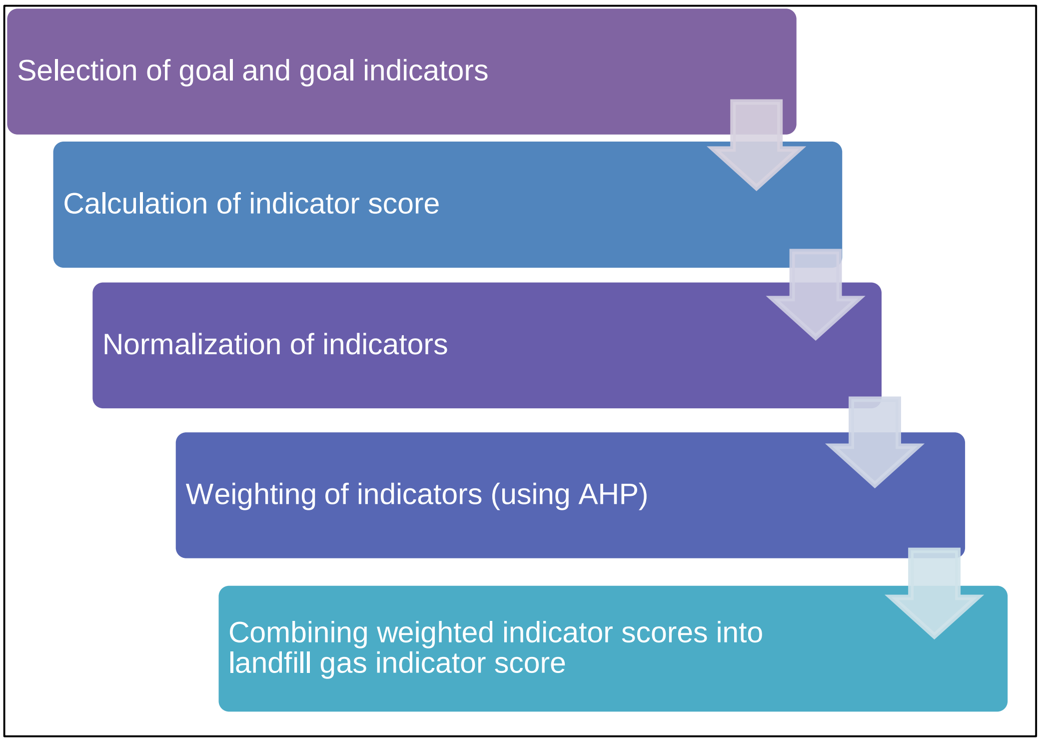

Figure 7. The procedure for calculating landfill gas indicator scores in the DST using multi-criteria analysis, adapted from Krajnc and Glavic (2005a, 2005b) (AHP: Analytical Hierarchical Process).

3.2.3.1 Indicator selection

The indicators were selected according to their influence on methane generation as discussed previously and the availability of measured data for that indicator published in literature. Table 7 shows which indicators have been selected for the DST and which have not been included.

Table 7. Landfill gas indicators selected for the DST and omitted.

Landfill Gas Indicator	
Selected	**Omitted**
Moisture Content	Waste Density
Temperature	Waste Composition
pH	Nutrient Ratio
COD	Microbial population
BOD 5 day	Sulphate
BOD/COD ratio	Other heavy metals
Alkalinity as $CaCO_3$	
Chloride	
Ammonia-N	
Iron	
Zinc	
Ammonia-N (mg/L)	
Iron (mg/L)	
Zinc (mg/L)	

3.2.3.2 Calculating individual landfill gas indicator scores and normalizing the indicator values

The landfill gas indicator score is calculated for each individual indicator initially on an unweighted basis (Equation (3-2)). The score is normalized against the average ideal value and lower boundary of the ideal value range in order to compare and aggregate different units. The ideal values for each indicator are given in Table 1 and Table 2.

$$I_{N,it} = \frac{I_{A,it} - I_{V,i}}{I_{V,i} - I_{L,i}} \qquad \textbf{(3-2)}$$

Where $I_{N,it}$ is the normalized indicator *I* for time t and $I_A$is the actual indicator value, I_V is the average ideal value and $I_L$is the lower boundary of the ideal value range.

The scores used to define the boundaries for the traffic light system are based on literature review evidence (section 2.1) of optimal methane generation boundaries for green values and are assigned arbitrary levels for yellow and red scores.

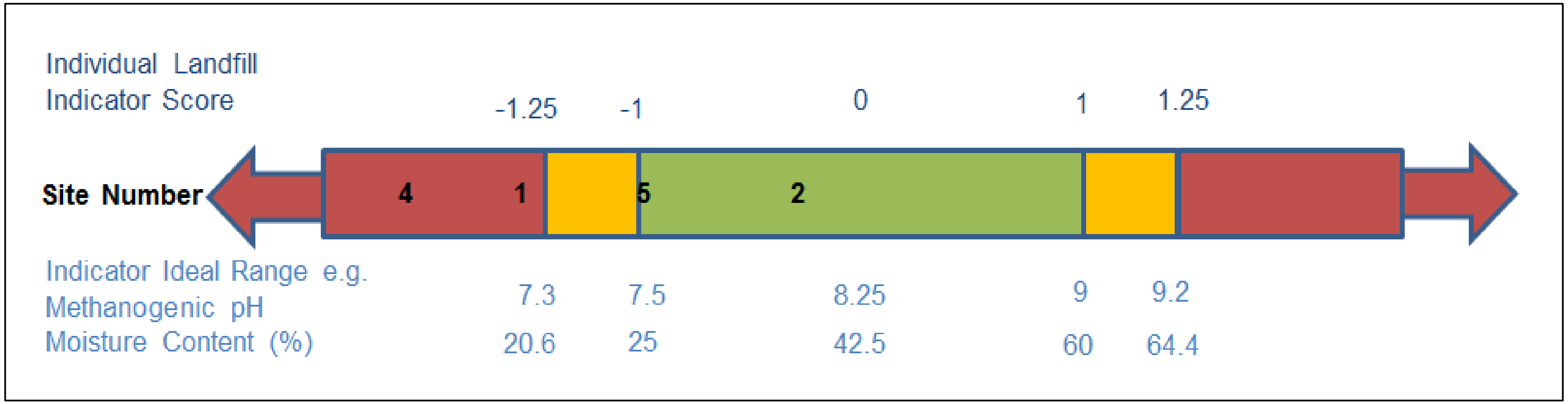

Figure 8. An example of the traffic light system for the two landfill gas indicators. The scores reflect the proximity of the user input value for each site to the ideal average value relative to the size of the ideal range.

It is important that the score is relative to the size of the boundary as a small change in one indicator could have a much larger effect than another if the boundary was smaller. The scores are given red, green and yellow traffic light symbols within the DST which are dependent on the boundary levels for the scores set (Figure 8 and Table 8). The boundary levels are based on the ideal value range for each indicator. However, the model can be updated if necessary by suitably knowledge users to alter the boundary levels as deemed necessary. So, for pH in methanogenic conditions the ideal lower and upper values are 7.5 and 9 and these values are hence the boundaries for the green traffic light. The values are normalized using equation (4-5) to give scores of -1 and 1 for the lower and upper boundaries. Hence, the average ideal value, for methanogenic pH this is 8.25 is assigned a score of 0. The yellow zone encapsulates a score greater than 1 and -1 but less than 1.25 and -1.25. For the methanogenic pH indicator this is 7.3 – 7.5 and 9-9.2 respectively. Scores greater than this on both positive and negative scales are given a red traffic light. Whilst the pH scale differs from the other parameters being logarithmic as opposed to linear, the same boundaries are used as the scores are normalised by the dividing the difference between actual and optimum scores by the range of the optimum boundaries.

Table 8. A description of the traffic light system for individual and total landfill gas indicator scores. Boundary levels are set by the ideal range for each indicator.

Traffic Light	Score Boundary	Description
Green	Between -1 and 1.	Indicator is within accepted range for good methane production.
Yellow	Between -1.25 and -1 and between 1 and 1.25.	Indicator is outside the accepted range and close monitoring is necessary.
Red	Greater than -1.25 and greater than 1.25.	Indicator is well outside the accepted range and remedial action is necessary.

3.2.4 Calculating the total weighted landfill gas indicator score

3.2.4.1 Normalizing the indicators

The indicators are normalized during the procedure to calculate individual landfill indicator scores.

3.2.4.2 Weighting

Each parameter is then weighted according to its influence on the required objective such as pH having a high influence on the goal of methane maximisation. There are many different methods of weighting parameters or indicators such as multi attribute utility theory and a linear additive model (Dodgson et al., 2009). The AHP was chosen which provides a straightforward and fast method of calculating the relative weights of each parameter (Krajnc and Glavič, 2005b; Krajnc and Glavič, 2005a).

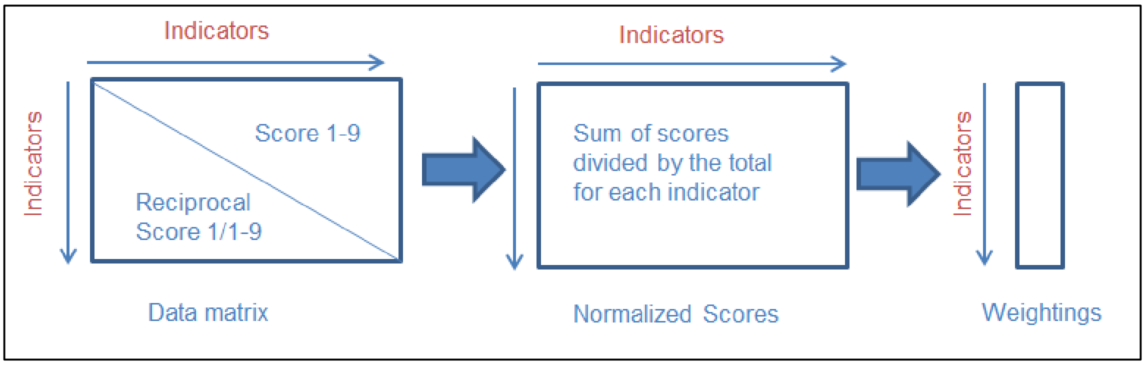

Figure 9. The analytical hierarchical process calculation for weighting parameters influencing methane output.

The AHP uses a linear additive model which gives a value score for an option for each criterion, multiplies this by the weight of the criteria and sums the scores together (Saaty, 1987) (Figure 9, Table 9 and Table 10). The AHP varies from other linear additive models by using pairwise comparison of criteria to assign weights (Saaty, 1987; Vaidya and Kumar, 2006).

Default scores from 1-9 for each indicator are provided but can be updated by the user according to site specific information of landfill gas indicator influence on methane generation (Figure **10**). Default values were discussed and provided by a panel of one academic and one professional in the waste industry who operates a landfill site.

Table 9. The AHP process for calculating the default weights for the landfill gas indicators. The first stage is to make pairwise comparisons for each indicator assigning a score of 1-9. The reciprocal score is used for the reciprocal pairwise comparison.

	Moisture Content	Alkalinity as $CaCO_3$	pH	BOD/COD ratio	COD	BOD	Temp	Zinc	Iron	Chloride	Ammonia
Moisture Content	1	2	3	4	5	5	6	9	9	9	9
Alkalinity as $CaCO_3$	0.5	1	3	4	5	5	5	7	7	7	8
pH	0.33	0.33	1	3	4	4	5	7	7	7	8
BOD/COD ratio	0.25	0.25	0.33	1	3	3	4	6	6	6	6
COD	0.2	0.2	0.25	0.33	1	2	3	5	5	5	5
BOD	0.2	0.2	0.25	0.33	0.5	1	3	5	5	5	5
Temp	0.17	0.2	0.2	0.25	0.33	0.33	1	3	3	3	3
Zinc	0.11	0.15	0.14	0.17	0.2	0.2	0.33	1	1	1	0.2
Iron	0.11	0.15	0.14	0.17	0.2	0.2	0.33	1	1	1	0.2
Chloride	0.11	0.14	0.14	0.17	0.2	0.2	0.33	1	1	1	0.17
Ammonia	0.11	0.13	0.13	0.17	0.2	0.2	0.33	5	5	6	1
TOTAL	3.09	4.74	8.59	13.66	19.63	21.13	28.33	50	50	51	45.57

Table 10. The AHP normalization process for calculating the default weights for the landfill gas indicators.

	Moisture Content	Alkalinity as $CaCO_3$	pH	BOD/COD ratio	COD	BOD 5 day	Temp	Zinc	Iron	Chloride	Ammonia	Weighting
Moisture Content	0.32	0.42	0.35	0.29	0.25	0.24	0.21	0.18	0.18	0.18	0.20	0.26
Alkalinity as $CaCO_3$	0.16	0.21	0.35	0.29	0.25	0.24	0.18	0.14	0.14	0.14	0.18	0.21
pH	0.11	0.07	0.12	0.22	0.20	0.19	0.18	0.14	0.14	0.14	0.18	0.15
BOD/COD ratio	0.08	0.05	0.04	0.07	0.15	0.14	0.14	0.12	0.12	0.12	0.13	0.11
COD	0.06	0.04	0.03	0.02	0.05	0.09	0.11	0.10	0.10	0.10	0.11	0.07
BOD	0.06	0.04	0.03	0.02	0.03	0.05	0.11	0.10	0.10	0.10	0.11	0.07
Temperature	0.05	0.04	0.02	0.02	0.02	0.02	0.04	0.06	0.06	0.06	0.07	0.04
Zinc	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.00	0.02
Iron	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.00	0.02
Chloride	0.04	0.03	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.00	0.02
Ammonia	0.04	0.03	0.01	0.01	0.01	0.01	0.01	0.10	0.10	0.12	0.02	0.04

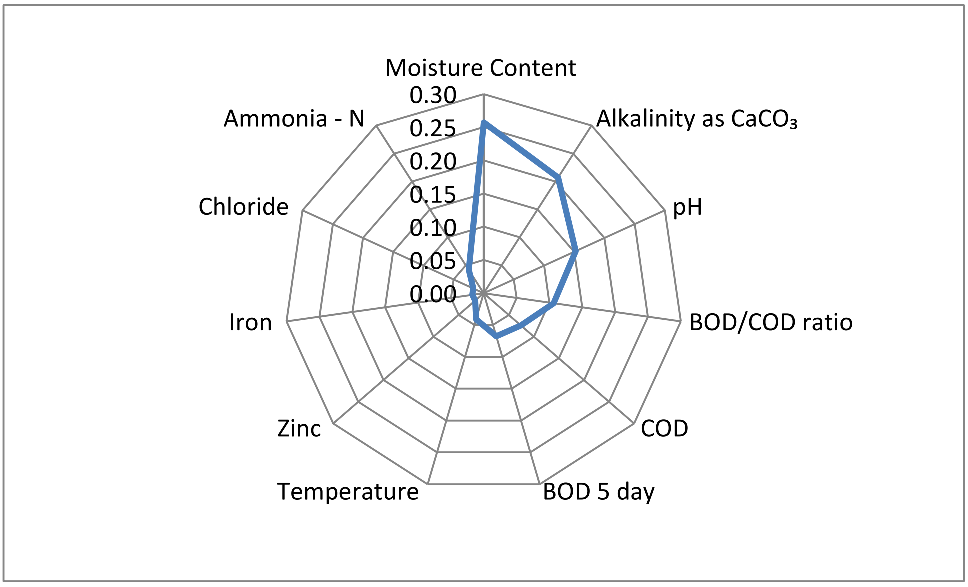

Figure 10**. The default weights for each landfill gas indicator used in the DST.**

3.2.4.3 Combining the weighted scores

The individual landfill gas indicator scores are multiplied by the weighting for each indicator, given an absolute value and summed to give the total weighted landfill gas indicator score for each site (Equation (3-3)). This provides a useful summary of how much the site varies from ideal values for methane generation over all indicators. The weighted scores are given an absolute value before being summed so as to show the total deviation from the ideal which is not negated by negative values. If positive and negative scores were summed there is potential for each score to cancel each other out to the average ideal value score (0) even if not the case.

$$Total\ Landfill\ Gas\ Indicator\ Weighted\ Score = \sum_{it}^{n} W_i \times |I_{N,it}| \quad \textbf{(3-3)}$$

Where:

$$\sum_{i}^{n} W_i = 1$$

$$W_i \geq 0$$

Where I: Individual landfill gas indicator score; N: Normalized indicator; W: Weighting and T: Time.

3.3 Landfill methane generation remedies

After a traffic light has been given to each methane output score or landfill gas indicator, the DST allows the user to view the cause and effect of an indicator having a red or yellow traffic light and highlights potential remedies for that indicator to produce a higher methane output rate (Table 11). This information is taken from established literature sources which are displayed in the tool. Some remedies mentioned in the table are restricted by the lack of ability to apply them retrospectively including reducing waste density and a mixture of wastes added. The remedy most used at a field scale level to improve overall methane generation is leachate recirculation. This aspect of the DST is intended to enhance the general understanding of the effect of each indicator on methane output production and possible remedies. It is not intended as comprehensive advice on how to resolve landfill methane generation issues. Potential remedies need to be assessed on a site-specific basis.

Table 11. Potential remedies given in the DST for parameters with red or yellow traffic light scores. (adapted from Mali Sandip (2012), Mata-Alvarez (2003) and Christensen et al. (1996).

Indicator	Cause	Effect	Potential Remedies
Methane output	Potentially unknown if data for environmental indicators is not entered.	Lower than predicted methane output today and potentially in the future.	A general improvement of landfill methane generation can be sought by ensuring a mixed composition waste input in the absence of toxic agents and pH neutral leachate recirculation to enhance microbial activity. See below for more detailed remedial action for individual indicators.
Waste composition	Waste selection for landfill.	Organic overload or lack of substrate for biogas conversion. Imbalance of aceotgenesis and methanogenesis. Accumulation VFAs.	Mixture of waste types placed in landfills.
Density of waste	Amount of waste, waste placement.	Leachate pooling, waste saturation, poor nutrient distribution.	Pre-shredding of waste prior to landfill entry and the establishment of maximum cell loads.
Moisture content	Rainfall, permeability, leachate management engineering.	Excessive moisture can cause a microorganisms washout, reducing pH and methane production. However there is an exponential increase in gas between 25-60% moisture content. Limits oxygen content. Facilitates exchange of substrate, nutrients, buffer and microorganisms to prevent the build-up of VFAs and hydrogen.	pH neutral leachate recirculation to prevent stagnation or saturation.
pH/ alkalinity	Volatile fatty acids (VFA) build up.	Imbalance of acetogenesis and methanogenesis. Accumulation of volatile fatty acids due to the inability of methanogens to convert them to methane causes a fall in pH.	High alkalinity/pH: Addition of sodium bicarbonate/ calcium carbonate buffer to leachate for recirculation to achieve the optimum range for methanogen bacteria (around pH 7). Waste could also be pre-composted aerobically to skip the acetogenesis stage.

BOD/COD ratio	Lack of biodegradable substrate or an inhibited biodegradation process. (Ratio of biologically degradable to chemically oxidisable substrate. Reflects the degradability of organic carbon.)	Lower than predicted methane output today and potentially in the future.	Adjust waste input or consider alternative parameters for methanogenesis inhibition. Microbial seeding from sewage/ AD sludge. Introduction of gravel to increase surface area for microbial growth.
Temperature	Environmental conditions, leachate recirculation or air suction.	Methane yield increases with temperature. Temperature increases methane x100 by 20-30 degrees and 30-40 decrease. Self-enhancing.	Pre heat leachate or prevent aeration.
Fe, Zn, Cl	Presence of toxic agents/inhibitors including heavy metals, solvents, high levels of hydrogen, ammonia, sulphides.	Microbial inhibition. Imbalance of aceotgenesis and methanogenesis. Accumulation VFAs	Landfill dynamic equilibrium has the ability to regulate inhibitors naturally. Pre-screening of waste input or cell isolation to prevent dispersal. Iron present in waste acts as a sulphide sink.
Ammonia	Waste composition	High ammonia levels increases pH.	Adjust waste input.

4. Scenario testing

4.1 Scenarios

In the absence of real monitored data, a series of scenarios are used to demonstrate how the DST can be used to assess good, average and poor landfill site gas performance and provide suggestions for improvement. Table 12 displays the landfill gas, leachate and waste parameters for each site used in the DST.

- Sites 1 and 2 are examples of landfill sites with good landfill methane generation i.e. high methane output rates and largely optimal landfill environment parameter measurements.
- Site 3 has an average landfill methane generation performance and
- Sites 4 and 5 represent landfill sites with poor landfill methane generation performance below the ideal methane output rate.

Each site represents a landfill site built in different years and accepting differing amounts of waste in the UK. Each site is analysed for landfill methane generation in one year – 2012 in the scenario testing.

Table 12. Waste acceptance, gas, leachate and waste data for five example landfill sites - Sites 1-5.

Site Number	1	2	3	4	5
Waste Input					
Landfill Open Year* (YYYY)	1986	1998	2005	1992	1989
Closure Year (YYYY)	2009				2006
Year of Analysis* (YYYY)	2012	2012	2012	2012	2012
Age of site at year of analysis (years)	26	14	7	20	23
Accepted Waste Mass (tonnes)*					
YEAR					
0	200,000	50,000	150,000	10,000	100,000
1	200,000	20,000	150,000	20,000	100,000
2	200,000	30,000	150,000	30,000	100,000
3	200,000	100,000	150,000	40,000	100,000
4	200,000	90,000	150,000	50,000	100,000
5	200,000	106,000	150,000	60,000	100,000

6	200,000	122,000	150,000	70,000	100,000
7	200,000	138,000	150,000	80,000	100,000
8	200,000	154,000	150,000	90,000	100,000
9	200,000	170,000	150,000	100,000	100,000
10	200,000	186,000	150,000	110,000	100,000
11	200,000	202,000	150,000	120,000	100,000
12	200,000	218,000	150,000	130,000	100,000
13	200,000	234,000	150,000	140,000	100,000
14	200,000	250,000	150,000	150,000	100,000
15	200,000	266,000	150,000	160,000	100,000
16	200,000	282,000	150,000	170,000	100,000
17	200,000	298,000	150,000	180,000	
18	200,000	314,000	150,000	190,000	
19	200,000	330,000		200,000	
20	200,000	346,000		210,000	
21	200,000	362,000		220,000	
22	200,000	378,000		230,000	
23	200,000	394,000		240,000	
24		410,000		250,000	
25		426,000		260,000	
26		442,000		270,000	
27		458,000		280,000	
28		474,000		290,000	
29				300,000	
30				310,000	
Landfill Gas					
Total Landfill Gas Output (m^3/yr)*	30,000,000	20,000,000	5,000,000	5,000,000	3,000,000
Methane Content (%)		44	54		
Methane Output (m^3/yr)	12500000	8800000	2700000	2500000	1500000
Waste Characteristics					
Potential Methane Generation Capacity (m^3/Mg)*	100	100	100	100	100
Moisture Content (%)	40	50	60	70	10
Temperature (°C)	30	30	50	10	10
Leachate					
pH	7.2	8.1	#	6.4	7.5
COD (mg/L)	6,000	3,000	5,000	2,000	5,000
BOD 5 day (mg/L)	180	180	#	200	#
BOD/COD ratio	0.08	0.04	0.05	0.03	0.07
Alkalinity as $CaCO_3$ (mg/L)	700	600	900	700	100
Chloride (mg/L)	1000		3000	4000	2000
Ammonia-N (mg/L)	750	700	800	900	1000

Iron (mg/L)	17	11	#	1	18
Zinc (mg/L)	0.1	0.2	0.1	0.3	#

4.2 Results and Interpretation

The DST provides a results summary in a graphical and tabular format (Figure 11 and Figure 12). The methane output and total landfill gas indicator scores are displayed along with the traffic light assigned to each score. The breakdown of how scores are calculated for each site is discussed below**.**

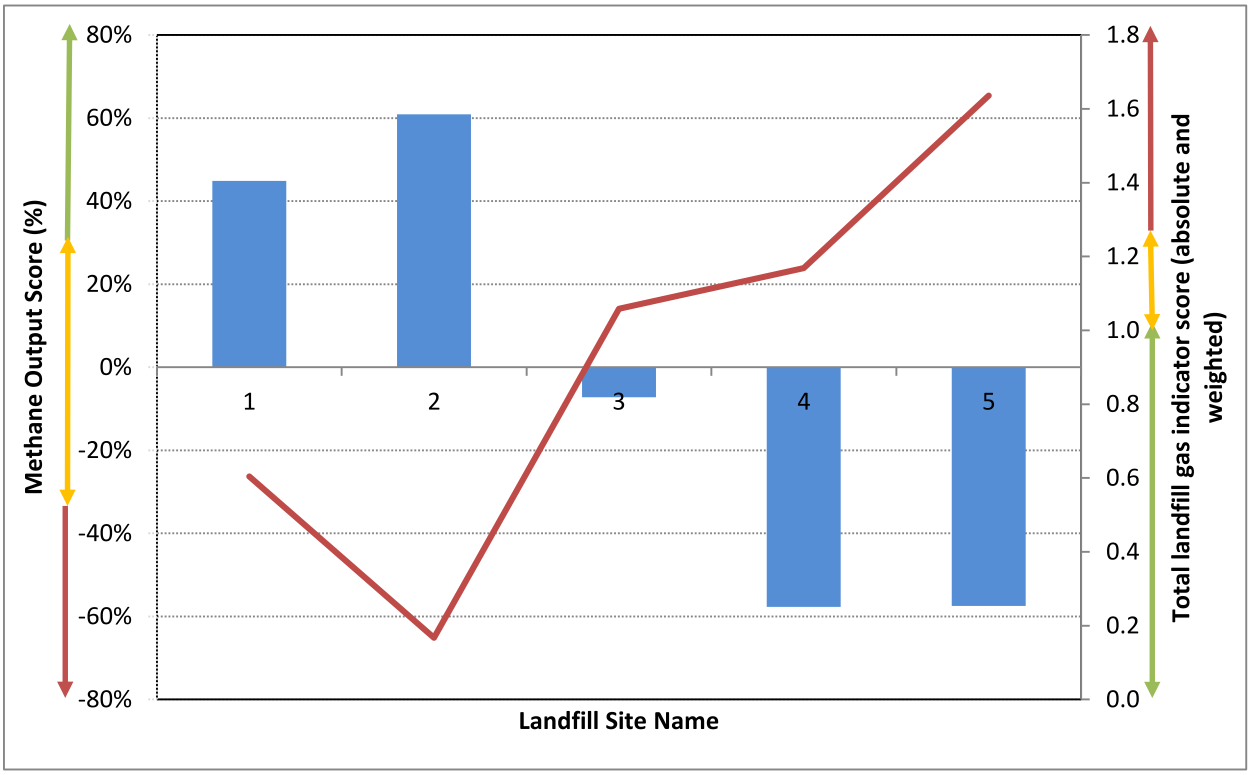

Figure 11. Site results graph including the methane output score and total landfill gas indicator score for sites 1-5. The methane output score is plotted on the left hand scale and the total landfill gas indicator score is plotted on the right hand scale. The traffic light colour boundaries are shown with arrows on the scales.

Cell Name	1	2	3	4	5
Methane Output Score (%)					
Methane Output	44.8%	60.9%	-7.2%	-57.7%	-57.5%
Landfill Gas Indicator Scores					
Moisture Content	-0.1	0.4	1.0	1.6	-1.9
Alkalinity as $CaCO_3$	1.0	0.0	3.0	1.0	-4.0
pH	-1.4	-0.2 #		-2.5	-1.0
BOD/COD ratio	0.2	-0.2	-0.1	-0.3	0.1
COD	1.5	0.0	1.0	-0.5	1.0
BOD 5 day	0.0	0.0 #		0.1 #	
Temperature	0.0	0.0	2.0	-2.0	-2.0
Zinc	-0.3	-0.2	-0.3	-0.2 #	
Iron	0.0	0.0 #		-0.1	0.0
Chloride	-0.5 #		0.4	0.9	-0.1
Ammonia - N	0.0	0.0	0.1	0.1	0.2
Total Landfill Gas Indicator Score (weighted and absolute)	0.6	0.2	1.1	1.2	1.6

Figure 12. DST results display including the traffic lights for each score.

4.2.1 Site 1

For site 1, the methane output is above predicted levels and therefore it receives a green traffic light (Table 13). A score of 44.8% shows that it is operating at 44.8% higher levels of methane output than predicted in the LandGEM model (Table 13). Therefore no action is necessary to remediate the site.

In order to understand what is happening within the landfill environment to achieve this score a breakdown of landfill gas indicators is also provided (Table 13). For site 1, most indicators are operating within the accepted range for optimal methane output. For example, a moisture content of 40% gives a score of -14.3% below the ideal average value for optimal methane output relative to the range of the ideal value for that indicator. Alkalinity is given a yellow traffic light which indicates that this indicator is just outside the ideal range for methane output and needs to be monitored (Table 8). COD and pH are given a red traffic light which indicates that they are well outside the ideal range of 7.5-9 as indicated in Table 2 and action needs to be taken to address this issue.

In the case of site 1, although the overall landfill score and weighted environmental indicator score has a green traffic light, some environmental indicators display red and yellow lights which can be addressed if wanted. This is due to the fact that methane generation is a complex and dynamic process which does not require all indicators to be green to produce green traffic lights. The COD indicator describes the amount of chemically oxidisable material in the leachate. This could be due to a problem within the landfill in the ability to degrade material but as the BOD and BOD/COD ratio scores are green this may indicate an error in the data provided. As the pH is below the ideal range for a methanogenic landfill site, potential remedial action could involve the recirculation of pH neutral leachate to assist the microorganisms present in regulating the pH to produce optimal environmental conditions for methane generation.

Table 13. The calculation of the DST results for site 1.

Parameter	Ideal Average	Ideal Range	Actual	Deviation from Ideal Average	W	S
Landfill Gas						
Methane Output (m^3/yr)	10,356,453	-	15,000,000	44.8%	-	44.8 %
Landfill Gas Indicators						
Moisture Content (%)	43	35	40	-0.1	0.26	0.0
Alkalinity as $CaCO_3$ (mg/L)	600	200	700	1.0	0.21	0.2
pH	8	2	7	-1.4	0.15	0.2
BOD/COD ratio	0.06	0.20	0.08	0.2	0.11	0.0
COD (mg/L)	3,000	4,000	6,000	1.5	0.07	0.1
BOD 5 day (mg/L)	180	530	180	0.0	0.07	0.0
Temperature (°C)	30	20	30	0.0	0.04	0.0
Zinc (mg/L)	1	4	0	-0.3	0.02	0.0
Iron (mg/L)	15	277	17	0.0	0.02	0.0
Chloride (mg/L)	2,120	4,350	1,000	-0.5	0.02	0.0
Ammonia - N (mg/L)	740	2,150	750	0.0	0.04	0.0
Total Indicator Score (absolute and weighted)						0.6

W: weight; S: score.

4.2.2 Site 2

Site 2 records the highest methane output score at 60.9% higher than the ideal average of 4,470,453 m^3/yr calculated for that site (Table 14). Each landfill gas indicator measurement for the site is within each of the accepted ranges for optimal methane output. The total landfill gas indicator score of 0.2 is close to zero which indicates little deviation from the ideal average measurement. This site is therefore given green traffic lights for each parameter and no further action is necessary to enhance the methane output for the site.

Table 14. The calculation of the DST results for site 2.

Parameter	Ideal Average	Ideal Range	Actual	Deviation from Ideal Average	W	S
Landfill Gas						
Methane Output (m^3/yr)	5,470,453	-	8,800,000	60.9%		60.9%
Landfill Gas Indicators						
Moisture Content (%)	43	35	50	0.4	0.26	0.1
Alkalinity as $CaCO_3$ (mg/L)	600	200	600	0.0	0.21	0.0
pH	8	2	8	-0.2	0.15	0.0
BOD/COD ratio	0.06	0.20	0.04	-0.2	0.11	0.0
COD (mg/L)	3,000	4,000	3,000	0.0	0.07	0.0
BOD 5 day (mg/L)	180	530	180	0.0	0.07	0.0
Temperature (°C)	30	20	30	0.0	0.04	0.0
Zinc (mg/L)	1	4	0	-0.2	0.02	0.0
Iron (mg/L)	15	277	11	0.0	0.02	0.0
Chloride (mg/L)	2,120	4,350	0	0.0	0.02	0.0
Ammonia - N (mg/L)	740	2,150	700	0.0	0.04	0.0
Total Indicator Score (absolute and weighted)						0.2

W: weight; S: score.

4.2.3 Site 3

Site 3 was initially described as a site with an average landfill methane generation performance. The DST corroborated this assertion and calculated that the methane output score was -7.2% which is within the yellow, average, traffic light boundary indicating that methane output levels are currently below predicted levels and landfill gas indicators with red and yellow traffic lights need to be monitored (Table 15). The total landfill gas indicator score was calculated at 1.1 which is marginally above the boundary for optimal methane generation. This score is pushed outside of the green traffic light zone largely due to the deviation of alkalinity and moisture content from the ideal range. These indicators are also the two most highly weighted and therefore any small deviation from the ideal range of measurements will give a high indicator score. This also indicates that it is important to monitor and potentially take action to bring these indicators within the ideal range. The alkalinity measured at the site is 900 mg/L which is 300 mg/L above the ideal average measurement. The individual indicator score is calculated as 3.0 (using equation (3-2)) which is well above the ideal boundary score of 1.0. The score is then weighted as 0.26 to sum the total landfill gas indicator score to give a contribution of 0.6. Addressing the issue of a high moisture content will improve alkalinity as the microorganisms are better able to regulate the pH within the landfill site (Mata-Alvarez, 2003). The saturation of a landfill site is potentially damaging to methane generation as microorganisms are unable to convert substrates to products (Christensen et al., 1996). The potential remedy for this issue is to maintain a leachate recirculation system within the landfill site which extracts excess moisture and feeds pH neutral leachate back into the site (Table 11).

Table 15. The calculation of the DST results for site 3.

Parameter	Ideal Average	Ideal Range	Actual	Deviation from Ideal Average	W	S
Landfill Gas						
Methane Output (m^3/yr)	2,909,330	-	2,700,000	-7.2%	-	-7.2%
Landfill Indicators						
Moisture Content (%)	43	35	60	1.0	0.26	0.3
Alkalinity as $CaCO_3$ (mg/L)	600	200	900	3.0	0.21	0.6
pH	8	2	0	0.0	0.15	0.0
BOD/COD ratio	0.06	0.20	0.05	-0.1	0.11	0.0
COD (mg/L)	3,000	4,000	5,000	1.0	0.07	0.1
BOD 5 day (mg/L)	180	530	0	0.0	0.07	0.0
Temperature (°C)	30	20	50	2.0	0.04	0.1
Zinc (mg/L)	1	4	0	-0.3	0.02	0.0
Iron (mg/L)	15	277	0	0.0	0.02	0.0
Chloride (mg/L)	2,120	4,350	3,000	0.4	0.02	0.0
Ammonia - N (mg/L)	740	2,150	800	0.1	0.04	0.0
Total Indicator Score (absolute and weighted)						1.1

W: weight; S: score.

4.2.4 Site 4

Site 4 represents a site with a poor landfill methane generation performance. The DST has given the site a red traffic light for the methane output score while the total landfill gas indicator score has received a yellow traffic light (Figure 12).

Methane output is 57.7% below the LandGEM predication for the waste input for the site which is well below the red traffic light boundary of -30% (Table 16). The landfill gas indicators that deviate from their ideal boundaries are: moisture content, alkalinity, pH and temperature. Whilst these factors are very important for methane generation, all other indicators are within the ideal boundaries and therefore bring the total landfill gas indicator score down to a yellow traffic light. Action needs to be taken for this site to improve landfill methane generation. Methane output can be enhanced by ensuring a mixed composition of waste input in the absence of toxic agents and pH neutral leachate recirculation to reduce moisture content, pH and alkalinity and enhance microbial activity (Table 11). The temperature is more difficult to improve in waste already in place but enhanced microbial activity from the aforementioned methods will produce heat from the reactions taking place. Other methods include the pre-heating of waste entering the site (Table 11).

Table 16. The calculation of the DST results for site 4.

Parameter	Ideal Average	Ideal Range	Actual	Deviation from Ideal Average	W	S
Landfill Gas						
Methane Output (m^3/yr)	5,914,614		2,500,000	-57.7%		-57.7%
Landfill Indicators						
Moisture Content (%)	43	35	70	1.6	0.26	0.4
Alkalinity as $CaCO_3$ (mg/L)	600	200	700	1.0	0.21	0.2
pH	8	2	6	-2.5	0.15	-0.4
BOD/COD ratio	0.06	0.20	0.03	-0.3	0.11	0.0
COD (mg/L)	3,000	4,000	2,000	-0.5	0.07	0.0
BOD 5 day (mg/L)	180	530	200	0.1	0.07	0.0
Temperature (°C)	30	20	10	-2.0	0.04	-0.1
Zinc (mg/L)	1	4	0	-0.2	0.02	0.0
Iron (mg/L)	15	277	1	-0.1	0.02	0.0
Chloride (mg/L)	2,120	4,350	4,000	0.9	0.02	0.0
Ammonia - N (mg/L)	740	2,150	900	0.1	0.04	0.0
Total Indicator Score (absolute and weighted)						1.2

W: weight; S: score.

4.2.5 Site 5

Site 5 also represents a site with methane generation below expected levels. The DST methane output score is -57.5% which is well below the LandGEM prediction for this site and it is given a red traffic light (Table 17). The total landfill gas indicator score is also given a red traffic light at 1.6 which is mainly affected by the low moisture content and alkalinity measurements for the site. Moisture content at 10% is well below the ideal boundary of 25-60% (Table 1) and as it is given a high weighting contributes an absolute score of 0.5 to the total. Alkalinity is also below the ideal boundary for a landfill in methanogenic conditions of 500-700 mg/L (Table 2) and contributes 0.8 to the total landfill gas indicator score. Remedial action is therefore necessary for this site to improve the methane output rate, alkalinity and moisture content. The potential remedies for these indicators have already been highlighted for previous sites.

Table 17. The calculation of the DST results for site 5.

Parameter	Ideal Average	Ideal Range	Actual	Deviation from Ideal Average	W	S
Landfill Gas						
Methane Output (m^3/yr)	3,527,910		1,500,000	-57.48%		-57.5%
Landfill Gas Indicators						
Moisture Content (%)	43	35	10	-1.9	0.26	-0.5
Alkalinity as $CaCO_3$ (mg/L)	600	200	200	-4.0	0.21	-0.8
pH	8	2	8	-1.0	0.15	-0.2
BOD/COD ratio	0.06	0.20	0.07	0.1	0.11	0.0
COD (mg/L)	3,000	4,000	5,000	1.0	0.07	0.1
BOD 5 day (mg/L)	180	530	0	0.0	0.07	0.0
Temperature (°C)	30	20	10	-2.0	0.04	-0.1
Zinc (mg/L)	1	4	0	0.0	0.02	0.0
Iron (mg/L)	15	277	18	0.0	0.02	0.0
Chloride (mg/L)	2,120	4,350	2,000	-0.1	0.02	0.0
Ammonia - N (mg/L)	740	2,150	1,000	0.2	0.04	0.0
Total Indicator Score (absolute and weighted)						1.6

W: weight; S: score.

4.3 Discussion

The scenario testing proved that the DST can be reliably used to highlight good, average and poor performance as it produced scores for each site that were consistent with the initial scenario assessment (Figure 11). However, the use of real monitoring data would have tested the validity of the model. The methane output score was over 30% (green traffic light) for both well performing sites 1 and 2 and below -30% (red traffic light) for both poor performing sites 4 and 5 with site 3 tending to 0% (yellow traffic light) (Figure 12). The use of a more accurate landfill gas model within the methane output score when developed in the future would improve the overall reliability of the DST and the scores it produces. This includes the accurate choice of potential methane capacity and degradation constant values according to what waste is emplaced in the site. The inherent problem of the DST is its reliance on accurate data input by the user which is difficult to produce in the waste industry due to a historic lack of data recording. However, newer landfills and newer models with better data recording practices will increase the reliability of the model.

On a different scale, the total landfill gas indicator scores for each site deviated above the optimal range boundary of 1.0 for sites 3-5 and remained between 0 and 1.0 for sites 1 and 2. Site 2 produced both the highest methane output score and total landfill gas indicator score which proves the reliability of the DST as indicator scores within the optimal ranges should enhance methane generation. The total landfill gas indicator score however hides the deviation of individual indicators which in some cases are given a red traffic light when the total landfill gas indicator score is given a green traffic light for example in site 1 (Table 13). This is due to the fact that landfill processes are complex and dynamic and while some indicators have a high influence on the methane output rate, others do not which is accounted for in the weighting mechanism of the tool. For example, optimal moisture content allows for the transportation of nutrients, microorganisms and intermediate products for enhanced biodegradation of waste to produce methane. The microorganisms necessary for the biodegradation of waste also need moisture to convert substrates into products at each stage of the process. Another important role of moisture content is to dilute biodegradation inhibitors such as sulphates and heavy metals. Hence, moisture content has an effect on all other landfill gas indicators in a facilitator role (Christensen et al., 1996). Alkalinity is also given a high weighting as it measures the ability of the landfill site to buffer changes in pH caused by biodegradation (Mata-Alvarez, 2003). Conditions too acidic or alkali retard the ability of microorganisms to convert substrates to degradation products. The BOD/COD ratio measures the amount of biodegradable substrate still available for degradation and is dependent on moisture content and alkalinity for the biodegradation to take place. The temperature is important to facilitate waste degradation but is given a lower weighting as it does not tend to vary significantly between landfill sites within similar climates (Robinson, 2007). Hence, each landfill gas indicator is dependent on each other indicator. The scenario testing showed that the parameters chosen for the DST only make a significant impact on the total landfill gas indicator score if they are weighted highly such as moisture content and alkalinity. Parameters such as heavy metal concentrations and temperature had a low impact on the overall score but are useful in terms of creating an overall picture of the state of the landfill site. Additional parameters could be added to the DST such as microbial population and the nutrient ratio within the site which would add further understanding to the methane generation capacity of a site. However this would add further complexity to the DST and this data is not readily available from landfill operators currently. The weightings of the parameters therefore have a significant influence on the total landfill gas indicator score. The MCA panel of one industry professional and one industry academic added beneficial field-scale knowledge to the model. An extended panel of experts and industry professionals would enhance the validity of the weightings produced in this model.

4.4 Cautionary Notes

The DST provides a framework for the assessment of landfill methane generation. It can be used to inform decision makers of the evolutionary stage of the landfill site, to track landfill methane generation over time and compare and rank a set of landfill sites. It also has the ability to early on flag up specific problems within a landfill site for methane generation and provides suggestions for potential remedial action. It has been designed to allow the user to adjust the settings due to the heterogeneous nature of landfill sites. For example, the methane potential in the landfill gas model can be adjusted to reflect specific site waste inputs. Also, the weightings of the landfill gas indicators can be altered to reflect landfill operator professional knowledge of which indicator affects landfill gas generation more than others at one site. Therefore, caution must be taken to note that with different model settings, the results are not comparable and advice for remediation is not necessarily supported by the authors. Several limitations are highlighted below which the user needs to be aware of when reviewing the tool results. Conservative estimates must be used in order to not overestimate methane generation.

4.4.1 Research Limitations

- The DST is based values taken from literature which need to be updated over time as new data becomes available to reflect modern landfill processes.
- The landfill gas model used in the DST, as with all landfill gas models currently available, is subject to an aforementioned wide error margin which needs to be taken into consideration when analysing the results.
- Landfill gas indicators ideal values are based on data from landfill sites in Germany in the 1980s which may not be representative of past and future landfill sites in different geographic locations.
- No sensitivity analysis has been performed on the landfill gas indicators to test how much one influences another due to a lack of field-scale data available for testing whilst existing influences are present and are mentioned previously.
- The weightings of landfill gas indicators for the DST are based on a small panel of one academic and one professional which could be expanded to increase the weighting’s validity.

4.4.2 Tool Limitations

- Any lack in data quantity or quality reduces the reliability and increases the error of the decision support tool.

- A user changing the model settings needs to be a professional and knowledgeable of landfill processes.
- Once a landfill site or cell is capped and closed, it is not re-opened which would allow oxygen into the site and hence disrupt the methanogenesis process.
- Landfill sites or cells average leachate, waste and gas measurements are assumed to be representative of the entire landfill site.
- Atypical waste input increases the tools inaccuracy as the landfill gas predications are based on typical inputs.
- The ideal value ranges for landfill gas indicators are taken from typical values at acetogenic and methanogenic sites. Therefore an assumption is made that these ranges translate to optimal methane generation conditions.
- Landfill leachate is assumed to develop from acetogenic to methanogenic conditions within 2 years (World Bank - ESMAP, 2004).
- Landfills are assumed to have not reached an aerobic stage and are less than 40 years old.

5. Conclusion

The results of the DST scenario testing described in this paper show how the tool can be easily used to by decision makers of landfill sites. If the user is able to take into account that any tool or model is underpinned by a set of simplified assumptions, and therefore is aware of its limitations, it could be used to understand and improve landfill methane generation.

Landfill gas production is a complex and dynamic process which provides a wide ranging and complex set of data to landfill site operators. No tool is currently available to integrate these datasets into a simple and clear set of scores for the landfill operator to base its decision on. The literature review highlighted that not only was this the case, but that it is possible to adopt well-established multi-criteria techniques and apply them to a landfill site to provide these scores. The tool has been shaped in terms of selecting which indicators are most important to landfill gas production by professional and academic experts to provide relevant and scientific information. Whilst this may introduce bias into the tool as opinions on which indicators are more influential than others may vary, the tool allows for the user to calculate its own weights. The tool is economically beneficial for landfill operators as it could be used to enhance profitable methane generation.

The tool provides a methane output score which measures the actual methane output rate against the prediction given by the LandGEM model for the waste it has accepted. This acts as an initial flag as to how well the site is performing overall. A set of landfill gas indicator scores are also provided which enables the decision maker to tap into what is happening within the landfill environment on an individual basis to give a good, average or poor methane output score. Each individual indicator is measured against a dataset of ideal values for each indicator at both the methanogenic and acetogenic stages of landfill evolution taken from literature. The most important indicators for methane generation are highlighted as moisture content and alkalinity. The total landfill gas indicator score uses MCA to provide an overview of the deviation of all the landfill gas indicators by multiplication of the individual landfill indicator scores by the weights calculated by AHP to each indicator. The weighted scores are then summed on an absolute basis. A set of traffic lights for the scores indicate whether the parameter is performing above, at or below expected levels and whether remedial action is necessary. This also increases bias in the tool as the boundary level for each traffic light is arguably variable. However, the tool is designed as a framework for which the user can alter the boundary levels for site-specific cases. A set of suggestions for remedial action for each parameter is provided in the tool to provide the decision maker with possible remedies to issues in methane generation.

The DST provides a useful framework for the assessment of landfill methane generation which can be updated over time as new indicator weightings, ideal values, landfill gas models and remedial methods become apparent.

5.1 Further work

Further work needed to improve the DST would involve creating a more recent and detailed set of ideal values for methane generation parameters which to use in the tool to compare landfill site measurements against. This would involve testing a wide range of landfill sites for leachate, gas and waste parameters at each evolutionary stage of a landfill. Field-scale data would also allow testing of the sensitivity of one methane generation indicator to another within the DST which is important for the validity of the tool. Also, an improved landfill gas model to test the methane output rate against would give a high accuracy to the tool. On a wider scale, more detailed measurement and reporting of landfill parameters over smaller time periods by landfill operators would enable a wider selection of landfill gas indicators to be analysed to improve the accuracy of the tool.

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APPENDICES

Appendix A Waste management journal article submission instructions

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Appendix B Landfill methane generation decision support tool (Microsoft Excel version on CD attached).

Appendix C Landfill methane generation decision support tool manual.

Landfill Methane Generation Decision Support Tool Manual

Harriet Emkes

Cranfield University
School of Applied Sciences
November 2013

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Preface

There is currently no decision support tool (DST) used in literature specifically for the assessment of landfill methane generation. The majority of tools available for landfill sites focus on long-term environmental risk management objectives in accordance with environmental regulations to control leachate and gas emissions from the landfill site. However, landfill gas generation is also important for landfill operators to monitor to maximise the methane output rate for sale as energy and to reduce the post-closure monitoring period. Methane gas (which makes up around 50% of landfill gas) is the lucrative component of landfill gas as it can be sold to provide energy in the form of gas, electricity and heat. Methane gas is an inherent product of landfilling waste but landfill operators can implement management techniques to increase the generation rate and quality.

This manual describes a unique DST to assess the performance of landfill gas generation at sites in the UK. The landfill gas decision support tool can be used to provide detailed, site-specific performance information for a given site. The tool assesses the methane generation of up to five sites in the "methane output score" using a comparison between predicted and actual rates. It also provides individual "landfill gas indicator scores" for the performance of indicators that influence methane generation including pH and moisture content. The landfill gas indicators are also given a total score based on multi-criteria analysis which weights the importance of each indicator on methane generation. The tool therefore aids the understanding of which landfill gas indicators are affecting methane output and in what way. Current and potential problem areas are highlighted by a traffic light system and potential remedies are suggested to improve landfill gas generation. However, the tool is only as accurate as is the accuracy of the data input by the user. Therefore, an awareness of the cautionary notes is necessary when interpreting the results of the DST.

Acknowledgements

The project was supervised by Dr Frédéric Coulon and Dr Stuart Wagland at Cranfield University and supported by Dr Stewart Davies, Viridor Ltd and the Engineering and Physical Sciences Research Council.

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1 Introduction

Landfill remains a widely used waste management method both in the UK and abroad regardless of its unsustainable nature due to the residues of more sustainable methods including incineration and anaerobic digestion needing to be placed somewhere. An average of 50% of local authority collected waste was sent to landfill in 2010/11 in the UK compared to an average of 40% in the EU-27 (Department for Environment, Food and Rural Affairs, 2013).

Landfill operators offset the cost of site management by the income generated from the sale of methane derived energy and gate fees. A typical 1MW landfill gas engine can earn £1,000 - £1,500 per day from government incentives and energy revenue which, compared with the costs of landfill gas extraction at £25,000 to £40,000 per hectare, means that steady profit can be made in a relatively short period of time (Strickland, 2010). Therefore, the economic success of a site is, in part, reliant on the landfill gas generation performance in terms of quality (high methane percentage) and quantity. Quality and quantity is reliant on landfill chemical, physical and biological processes turning carbon into methane gas which are described in more detail in subsequent sections. These processes require optimal environmental conditions to occur. If these processes are monitored an assessment can be made of landfill gas generation performance and suggestions can be made to improve landfill gas generation performance. This information provided to decision makers can help to improve understanding of landfill processes at the field-scale in order to make informed decisions about site management. A decision support tool (DST) is used to encompass this information by providing a robust, consistent, transparent and reproducible method for the decision making process (Sorvari and Seppälä, 2010).

Within the field of environmental science, DSTs are widespread in areas as diverse as sustainability and contaminated land management (Krajnc and Glavič, 2005b; Alvarez-Guerra et al., 2009; Balasubramaniam et al., 2007). However, there is currently no DST available specifically for the assessment of short-term landfill site gas generation performance. The majority of tools to help decision-making at landfill sites focus on the long-term environmental risk management objectives in accordance with environmental regulations. One environmental risk specific to landfill sites is methane gas emissions which is 21 times more potent than carbon dioxide in terms of greenhouse gas potential over 100 years (USEPA, 2013). Indeed, methane emissions from landfill account for 40% of the total methane emissions in the UK (Department for Environment, Food and Rural Affairs, 2007). For example, in England and Wales, a combined environmental risk and impact assessment approach is used by the Environment Agency to help decision makers to decide whether continued management is needed for landfill sites (Environment Agency, 2010). One criteria necessary to be met to halt landfill aftercare management is that methane must be at or less than 1.5% of total landfill gas and carbon dioxide must be at or less than 5% continually for a minimum of 2 years. The site must not have observed any topographical changes to ensure site settlement and stability.

1.1 Purpose of this Manual

This manual accompanies the DST as a guide to how it is used to assess landfill methane generation. The manual is intended to provide background information on landfill gas generation and an overview of how the tool was developed. It is based on five operational landfill sites based in the UK. The guide offers suggestions of remedies for poor landfill gas generation but does not offer any policy or financial guidance for alternative options.

1.2 DST Uses

The landfill DST can be used by landfill operators to:

- Assess the stage of evolution of a landfill site
- Compare and rank landfill sites
- Track landfill methane generation over time
- Provide an early warning system for landfill gas output
- Highlight areas of potential improvement within the landfill site
- Provide statistical information for the decision making process

- Indicate best landfill practices

1.3 Manual Outline

The manual provides a theory of landfill processes and methane gas generation in Section 2, providing the knowledge necessary for using and understanding the DST.

Section 3 provides a step by step guide to using the DST and entering the data necessary for landfill methane generation scores to be produced.

Section 4 provides information on how the scores are calculated.

Section 5 provides a step by step guide to viewing and interpreting the results from the DST.

Section 6 describes how to view remedies for methane enhancement necessary as highlighted in the DST.

Section 7 provides cautionary remarks for the use and interpretation of the DST results.

2 Theory of Landfill Processes

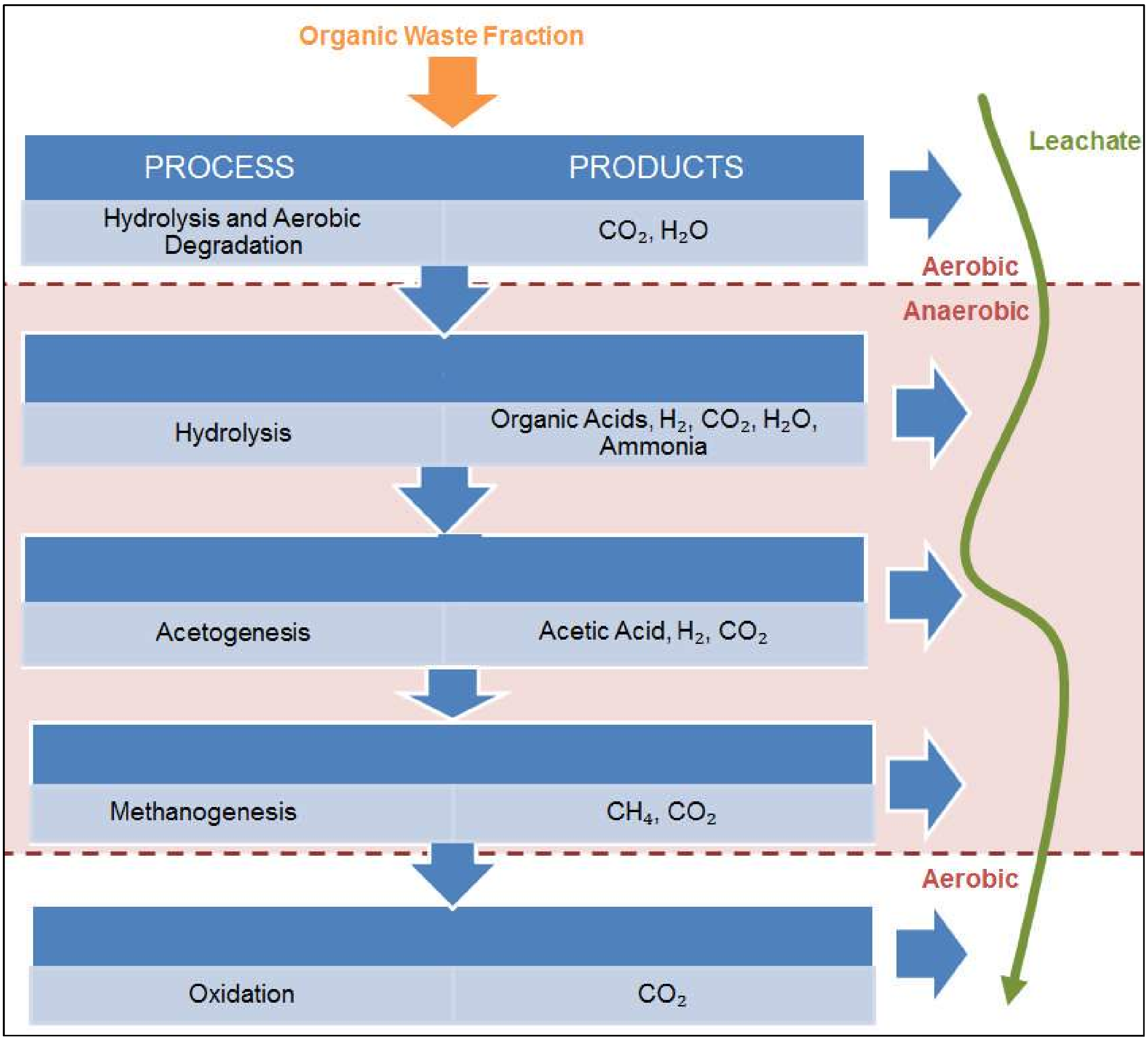

Figure 1. Organic waste fraction degradation processes in a landfill.

The processes that take place in landfills are widely described in literature through laboratory, field and theoretical experimentation (Mata-Alvarez, 2003; Themelis and Ulloa, 2007; Christensen and Kjeldsen, 1995). It is generally accepted that the organic waste fraction goes through a series of phases of degradation including hydrolysis, acetogenesis, methanogenesis and oxidation (Figure 1). The first stage of hydrolysis and the oxidation stage occur under aerobic conditions at the beginning and end of a landfills life whereas the intermediary stages take place under anaerobic conditions. This evolution is facilitated by various groups of microorganisms present in the landfill at different stages which convert specific substrates to intermediary products and then gas (Figure 2). Carbohydrates, proteins and fats are first hydrolysed to sugar, amino acids and long chain fatty acids (LCFA), respectively (all are soluble organic monomers). During acidogenesis these soluble organic monomers are converted to propionic acid, butyric acid and acetic acid as well as hydrogen and carbon dioxide. Acetogenesis takes place to convert LCFA to acetic acid, hydrogen and carbon dioxide. Methane is produced during methanogenesis both from acetic acid and from hydrogen and carbon dioxide

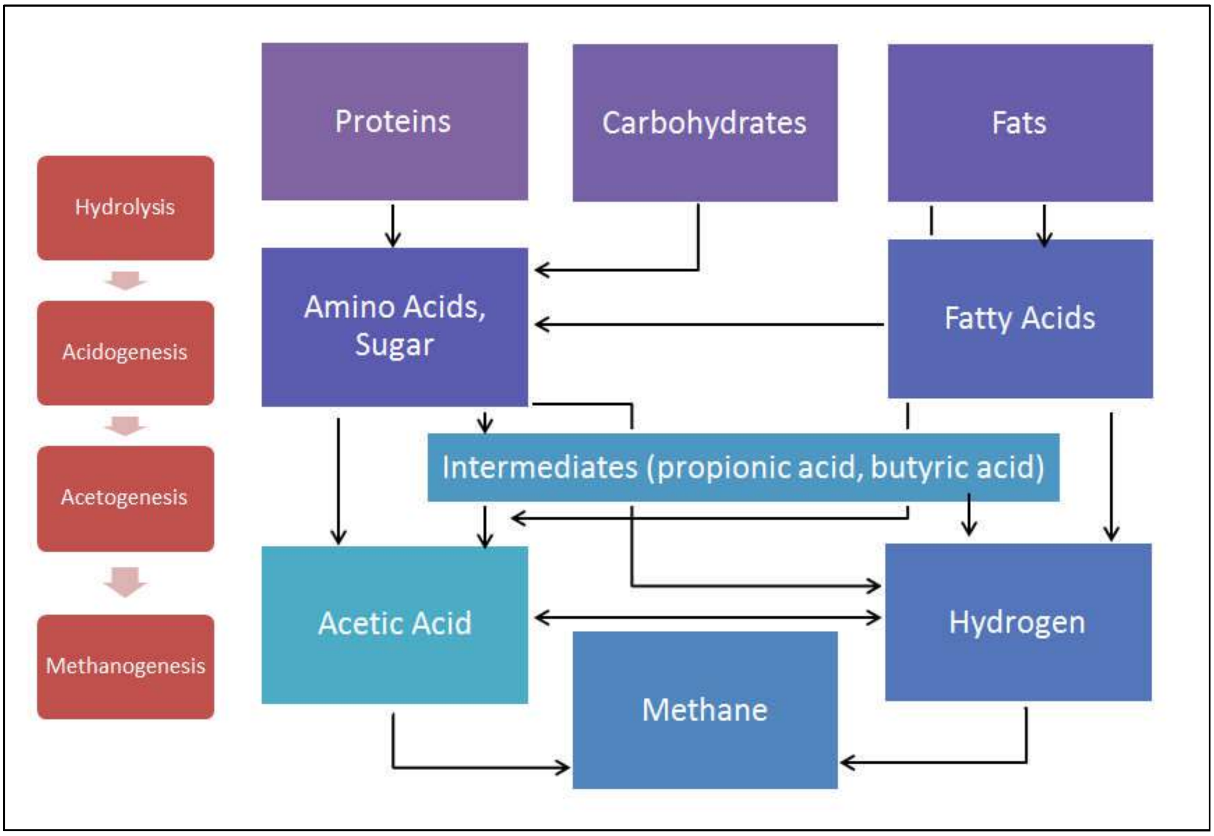

Figure 2. The degradation of proteins, carbohydrates and fats to methane.

These phases simultaneously produce variations in the environment within the landfill and produce changes in leachate, waste and gas composition (Figure 3). Leachate characteristics, or indicators, include pH, alkalinity, chemical oxygen demand (COD) and biochemical oxygen demand (BOD). The age at which a landfill site is expected to have turned to methanogenic conditions is within 2 years old and therefore the ideal range of most leachate indicators changes after this time in the DST (World Bank - ESMAP, 2004) (Table 2). For each indicator, a range of values is displayed for each stage. Due to the anaerobic nature of landfill sites, parameter values are very similar across a range of landfill sizes in Europe (Kjeldsen et al., 2002). Leachate values may not represent the entire cell and only that of the lowest section as the leachate percolates downwards through gravity. Therefore care must be taken when interpreting leachate values that the measured sample is representative of the site.

A stable landfill produces a dynamic equilibrium between all media. Kjeldsen et al. (2002) state that a strong relationship exists between leachate characteristics and the stage of landfill decomposition which is positive or negative depending on the indicator analysed.

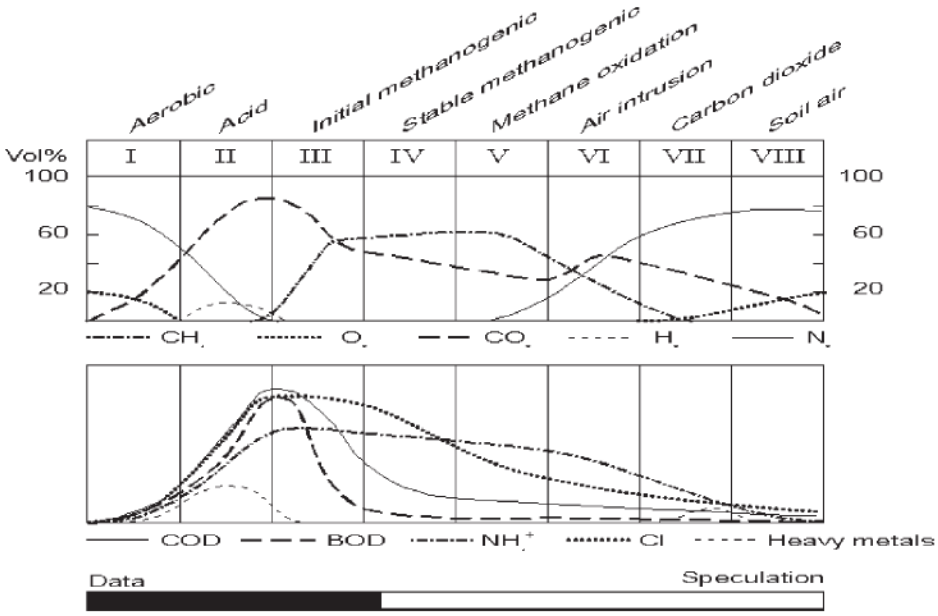

Figure 3. The evolution of a typical landfill site from aerobic to soil air stages including landfill gas and leachate values (Kjeldsen et al., 2002).

Therefore, this relationship can be used in a decision support tool to monitor landfill performance. Each landfill site produces similar values for leachate emissions due to the nature of landfill being closed entities (Robinson, 2007). Less is known about the time taken for each phase to occur due to environmental conditions varying widely between and within sites.

There are many indicators of landfill methane generation performance and therefore many that could be used in a DST (Table 1 and Table 2). The rate of methane output in terms of cubic meters per hour provides the closest current indicator of landfill stability and landfill gas optimisation (Mata-Alvarez, 2003). What it does not reveal, however, is what may or may not be happening in the landfill. Landfill gas indicators have been chosen for the DST to assess methane generation for their influence on methane generation and the availability of data available in literature.

Table 1. DST waste dataset tab showing moisture content and temperature boundaries for optimal methane generation (Christensen et al., 1996)

	Average	Range	Lower	Upper
Moisture Content (%)	42.5	35	25	60
Temperature (°C)	30	20	20	40

Table 2. DST Leachate dataset tab showing typical leachate composition upper and lower boundary and average values in acetogenic and methanogenic conditions (Ehrig, 1983; Ehrig, 1988; Tchobanoglous et al., 1993). Highlighted indicators have been selected for use in the DST.

	UK <2 years				UK >=2yrs				
	Acetogenesis				**Methanogenesis**				
Indicator	**Average**	**Range**	**Lower**	**Upper**	**Average**	**Range**	**Lower**	**Upper**	**Average**
pH	6.1	3	4.5	7.5	8	1.5	7.5	9	
Alkalinity as $CaCO_3$	5000	9000	1000	10,000	600	200	500	700	
BOD5	13000	36000	4000	40,000	180	530	20	550	
COD	22000	54000	6000	60,000	3000	4000	500	4500	
BOD/COD Ratio	0.58	0.4	-	-	0.06	0.2	-	-	
Sulfate	500	1680	70	1750	80	410	10	420	
Calcium	1200	24990	10	25,000	60	580	20	600	
Magnesium	470	1100	50	1150	180	310	40	350	
Iron	780	2080	20	2100	15	277	3	280	
Manganese	25	64.7	0.3	65	0.7	44.97	0.03	45	
Ammonia -N						2150	50	2200	740
Chloride						4350	150	4500	2120
Potassium									1085
Sodium									1340
Phosphorous									6

Cadmium									0.005
Chromium									0.28
Cobalt									0.05
Copper									0.065
Lead									0.09
Nickel									0.17
Zinc	5	119.9	0.1	120	0.6	3.97	0.03	4	

1. Waste composition

Waste composition reveals the potential methane output as degradable carbon content but is influenced by site specific factors (Environment Agency, 2004). Over time, as waste is degraded, the carbon content will reduce and therefore the age of waste entering a site also influences methane output. Waste introduced to the landfill site also contains bacteria, nutrients such as nitrogen and phosphorous and moisture which are essential to bacteria growth and subsequent methane production. However, complete waste composition data is often not available at landfill sites and is therefore not used as an indicator in this DST.

2. BOD/COD ratio

The BOD/COD ratio records the reduction in biodegradable matter in a landfill. A relatively high ratio can be expected at the initial stages of a landfill life as the organic waste fraction is still available to be degraded (Table 2). This will decrease towards zero over time as the waste is degraded and becomes inert. A low BOD/COD ratio indicates a low level of volatile fatty acids (VFAs) and relatively higher levels of humic and fulvic-like compounds as VFAs are consumed as quickly as they are produced in later, stable, stages of a landfills life (Kjeldsen et al., 2002). The BOD/COD ratio is a necessary but insufficient indicator of landfill methane generation performance as it does not take into consideration factors such as the variation in waste content throughout the site (Barlaz et al., 2002). Therefore, further indicators mentioned below are also needed to ensure a wider view of landfill methane generation.

3. Moisture Content

Kjeldsen et al. (2002) state that moisture content is the single most important parameter for gas production. Increase in moisture content from 25 to 60% increase biogas production for several reasons including transporting substrates, microbes and nutrients and diluting toxic substances (Table 1). However, saturation of a landfill above a 60% moisture content causes a drop or cessation of gas production as the microbes can no longer perform the conversions.

4. Leachate

Leachate is excess moisture in the landfill including the dissolution of soluble materials, the quality of which is a function of decomposition processes and other processes (Figure 4). This figure displays how leachate enters and exits a landfill site through rainfall and waste addition to leachate extraction and seepage through the liner.

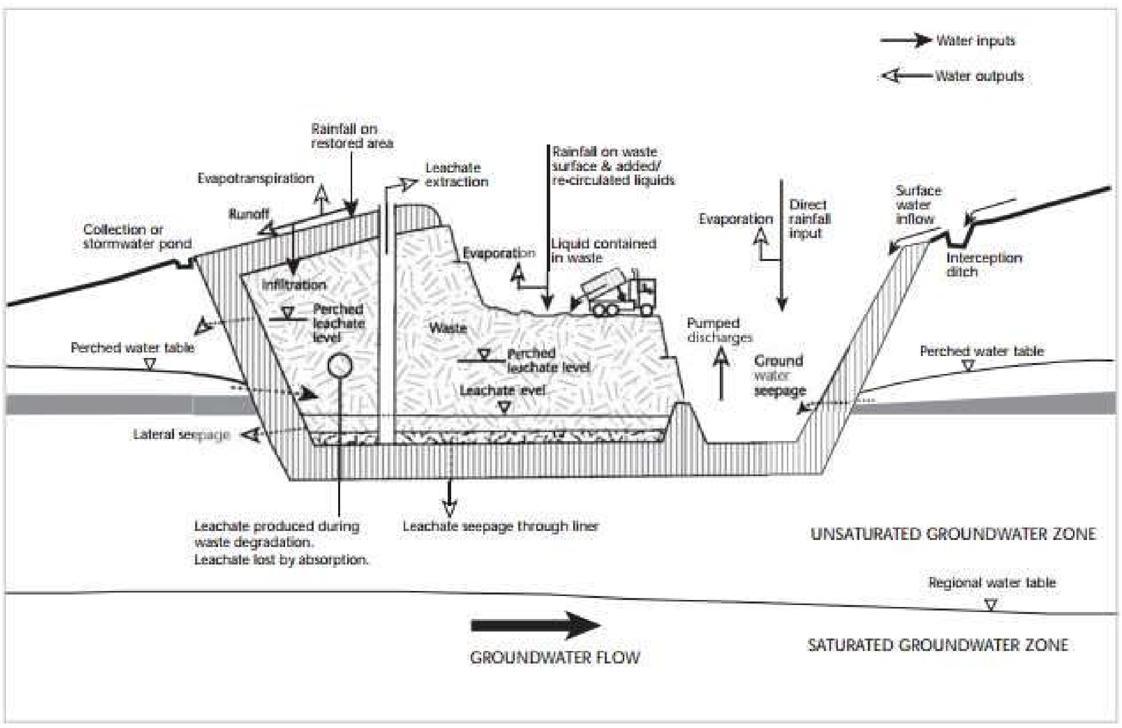

Figure 4. Landfill water balance including rainfall input and leachate output pathways. Taken from (Environment Agency, 2003).

Leachate values reveal the environmental conditions in the landfill but may not be representative of one point in time or the whole area of landfill (Barlaz et al., 2002). This is due to leachate only representing the deepest section of the landfill which will be more decomposed than at the top (Kjeldsen et al., 2002). Also, the hydraulic retention times varies widely between landfills and therefore leachate results may relate to different time periods across the site. The vertical infiltration rate of leachate also varies at different depths of a landfill (Figure 5).

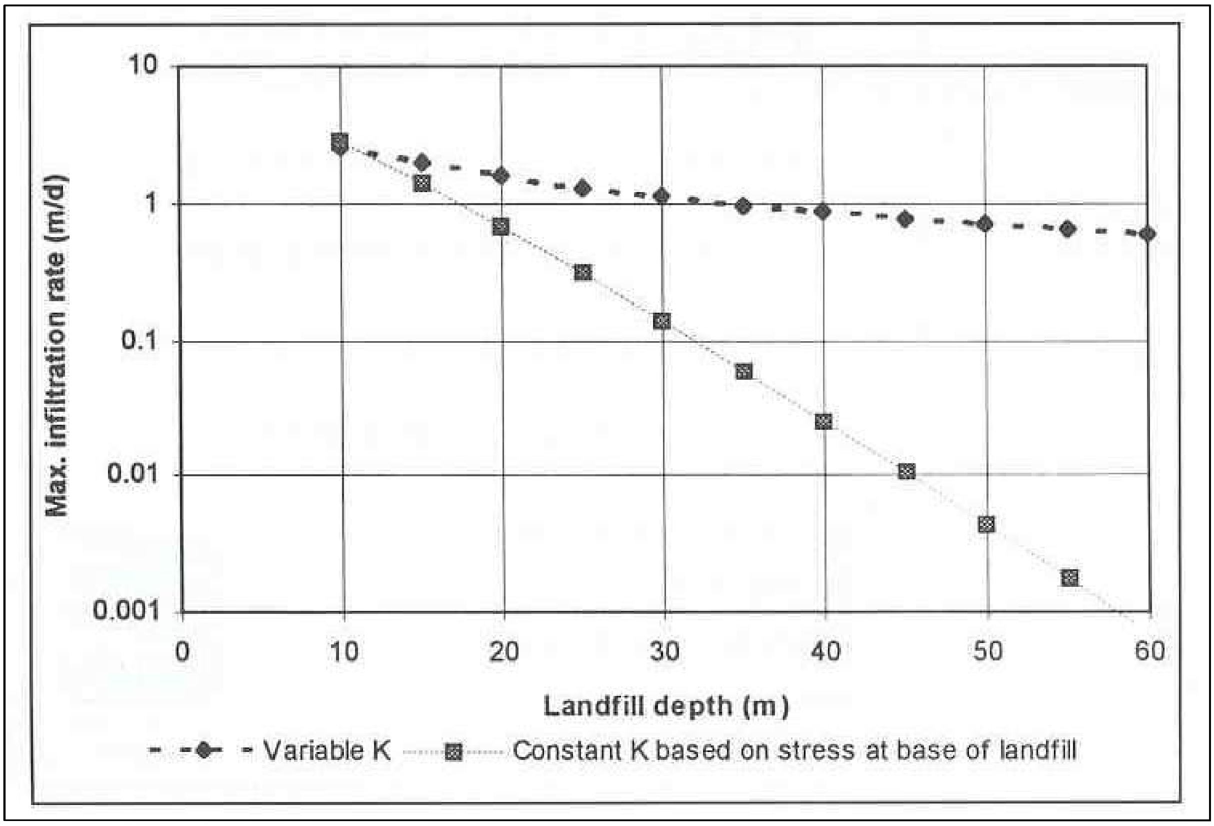

Figure 5 The effect of landfill depth on the vertical leachate infiltration rate. Taken from (Powrie and Beaven, 1998).

Leachate facilitates the pH and alkalinity of a landfill which are both essential to microbial growth and activity and buffering the increasing amount of acidic products in the early stages of the waste decomposition (Mata-Alvarez, 2003).

5. pH

pH is a measurement of the hydrogen ion concentration and indicates acidity (Mata-Alvarez, 2003). pH is described as a poor stand-alone indicator but does indicate the stage of waste degradation in a landfill site as the pH will be lowered by the production of LCFA.

6. Alkalinity

Alkalinity is the measurement of the ability of leachate to buffer sudden changes in acidity. It measures process stability more quickly than pH and is therefore assigned a higher weighting than pH in the weighting calculation (Mata-Alvarez, 2003).

7. Temperature

Heat is inherently generated within landfill sites during the conversion of waste to gases. Higher temperatures within a range of 20-40°C increase methane production (Christensen et al., 1996). Ambient temperatures outside a landfill site can also increase the temperature within a site but this reduces with lower depths of waste landfilled.

8. Inhibitors

Other parameters include the presence of heavy metals, sulphates and ammonia which, in high levels, are known inhibitors to anaerobic digestion (Chen et al., 2008).

2.1 Landfill methane generation Remedies

Completion of landfill degradation processes is made complex by the limited accessibility within a closed landfill site, the lack of knowledge in what is contained in each cell and the number of parameters involved in monitoring landfill stability. Also, no one parameter can be altered without affecting others. The most recognised method of completion is leachate recirculation which adds moisture content evenly and consistently throughout the landfill (Mali Sandip et al., 2012) which increases the moisture content from 15-20% to 40-50% (wet weight) and facilitates the transportation of nutrients, substrates and microorganisms (Kjeldsen et al., 2002). The leachate can also be added with a buffer solution to mitigate acidic effects of the acetogenesis phase to restore the balance for methanogenic bacteria to produce methane. By doing so it increases biogas production and site settlement as well as reducing leachate treatment costs (Benson et al., 2007).

Other less practiced and research methods include the pre-shredding of waste to ensure an even distribution of landfill components and pre-closure aeration. Aeration allows for some aerobic degradation of the waste which results in the avoidance of an acidic stage but the release of potential methane resources.

3 Using the DST

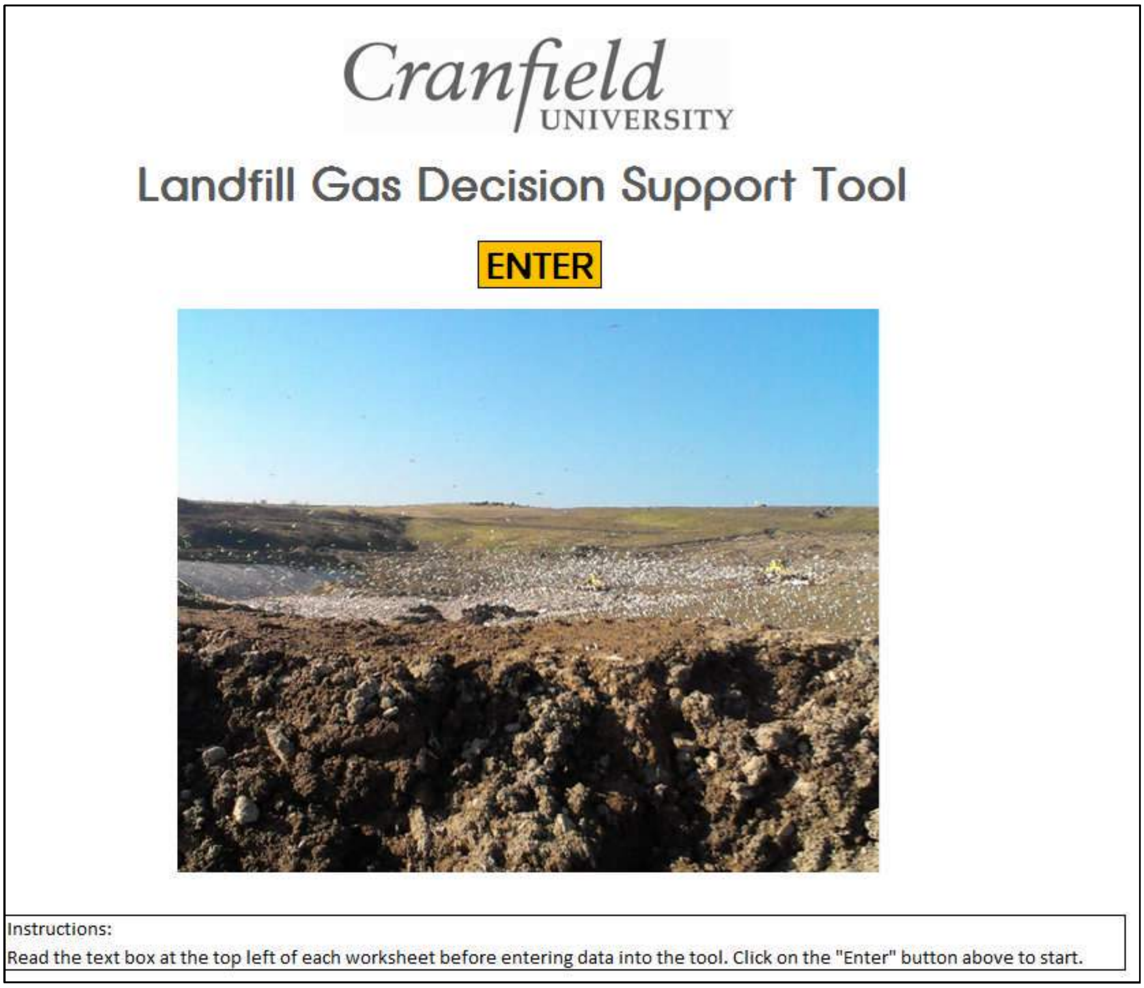

Figure 6. DST Introduction tab.

A decision support tool provides a robust, consistent, transparent and reproducible method for the decision making process (Sorvari and Seppälä, 2010). Multi criteria analysis is essential for the use of a decision support tool in a landfill situation due to the wide range of processes and parameters involved. It is a widely used and tested method in modern policy decision making such as deciding between which waste management technologies to use (Dodgson et al., 2009).

3.1 DST Interface

The tool was developed in the well-known Microsoft Excel 2010 software in order to be easy to use and accessible to the widest range of audience. The tool comprises a series of worksheets for the user to input data, to display results, remedies to landfill gas problems, calculations and underlying data. The user is able, at a basic level, to enter data for a specific site, view results and remedies. At a more advanced level further tabs are available to understand how the scores are calculated and certain model parameters can be altered. Excel provides the following useful features for a decision support tool:

- Separate worksheets for clear division of tool workings.
- Automatic Graphs and charts
- Hyperlinks for easy navigation

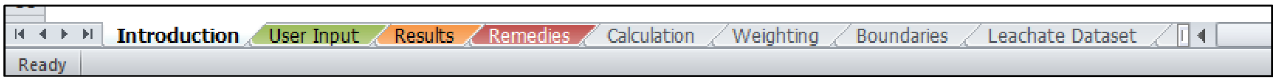

Figure 7. DST tabs are located at the bottom of the Excel screen.

A series of tabs are used for clear orientation of inputs, outputs, datasets and formulae (Figure 7). A small number of coloured tabs are necessary for the user to operate the tool:

- Introduction – tool instructions
- User Input – this is the only tab in which the user enters figures for each landfill
- Results – provided in graphical and tabular formats with an overall and parameter score
- Remedies – provide an indication of remedial techniques available for a low scoring parameter

The remaining white tabs are not necessary to use but are available to view to access the data and formulae behind the results. This provides transparency for the user in the model method.

3.2 Scenarios

A series of scenarios are used in this manual to demonstrate how to use the DST. Sites 1 and 2 are examples of landfill sites with good landfill methane generation. Site 3 has an average landfill methane generation performance and sites 4 and 5 represent landfill sites with poor landfill methane generation. The data for each site is displayed.

Table 3. Waste acceptance, gas, leachate and waste data for five example landfill sites - Sites 1-5.

Name of Landfill Site	1	2	3	4	5
Waste Input					
Landfill Open Year* (YYYY)	1986	1998	2005	1992	1989
Closure Year (YYYY)	2009				2006
Year of Analysis* (YYYY)	2012	2012	2012	2012	2012
Age of site at year of analysis (years)	26	14	7	20	23
Accepted Waste Mass (tonnes)*					
YEAR					
0	200,000	50,000	150,000	10,000	100,000
1	200,000	20,000	150,000	20,000	100,000
2	200,000	30,000	150,000	30,000	100,000
3	200,000	100,000	150,000	40,000	100,000
4	200,000	90,000	150,000	50,000	100,000
5	200,000	106,000	150,000	60,000	100,000
6	200,000	122,000	150,000	70,000	100,000
7	200,000	138,000	150,000	80,000	100,000
8	200,000	154,000	150,000	90,000	100,000
9	200,000	170,000	150,000	100,000	100,000
10	200,000	186,000	150,000	110,000	100,000
11	200,000	202,000	150,000	120,000	100,000
12	200,000	218,000	150,000	130,000	100,000
13	200,000	234,000	150,000	140,000	100,000
14	200,000	250,000	150,000	150,000	100,000
15	200,000	266,000	150,000	160,000	100,000
16	200,000	282,000	150,000	170,000	100,000
17	200,000	298,000	150,000	180,000	
18	200,000	314,000	150,000	190,000	
19	200,000	330,000		200,000	
20	200,000	346,000		210,000	
21	200,000	362,000		220,000	
22	200,000	378,000		230,000	
23	200,000	394,000		240,000	
24		410,000		250,000	
25		426,000		260,000	
26		442,000		270,000	

27		458,000		280,000	
28		474,000		290,000	
29				300,000	
30				310,000	
Landfill Gas					
Total Landfill Gas Output (m³/yr)*	30,000,000	20,000,000	5,000,000	5,000,000	3,000,000
Methane Content (%)		44	54		
Methane Output (m³/yr)	12500000	8800000	2700000	2500000	1500000
Waste Characteristics					
Potential Methane Generation Capacity (m³/Mg)*	100	100	100	100	100
Moisture Content (%)	40	50	60	70	10
Temperature (°C)	30	30	50	10	10
Leachate					
pH	7.2	8.1	#	6.4	7.5
COD (mg/L)	6,000	3,000	5,000	2,000	5,000
BOD 5 day (mg/L)	180	180	#	200	#
BOD/COD ratio	0.08	0.04	0.05	0.03	0.07
Alkalinity as $CaCO_3$ (mg/L)	700	600	900	700	100
Chloride (mg/L)	1000		3000	4000	2000
Ammonia-N (mg/L)	750	700	800	900	1000
Iron (mg/L)	17	11	#	1	18
Zinc (mg/L)	0.1	0.2	0.1	0.3	#

3.3 Setting up and running the tool

3.3.1 Opening the tool

Save the Microsoft Excel file “Landfill decision support tool” to your local drive. Open the file and save as an appropriate name for the site you wish to test. Left click on the “Introduction” tab at the bottom of the Excel screen page and read the instructions.

3.3.2 Entering parameter values for one landfill site

Left click on the “User Input” tab and read the instructions at the top left hand side of the worksheet. Data can now be entered from one site into column B

(Figure 8 and Figure 9). The following cells must be completed for the model to work:

- Name of Landfill Site:
- Landfill Open Year (YYYY)
- Year of Analysis (YYYY)
- Accepted waste mass (tonnes) for years 1,2,…n (maximum 30 years)
- Total landfill gas output (m^3/yr)
- Potential methane generation capacity (m^3/Mg)

	A	B
4	Name of Landfill Site	1
5		
6	Waste Input	
7	Landfill Open Year* (YYYY)	1986
8	Closure Year (YYYY)	2009
9	Year of Analysis* (YYYY)	2012
10	Age of site at year of analysis (years)	26
11	Accepted Waste Mass (tonnes)*	
12	YEAR	
13	0	200,000
14	1	200,000
15	2	200,000
16	3	200,000
17	4	200,000
18	5	200,000
19	6	200,000
20	7	200,000
21	8	200,000
22	9	200,000
23	10	200,000
24	11	200,000
25	12	200,000
26	13	200,000
27	14	200,000
28	15	200,000
29	16	200,000
30	17	200,000
31	18	200,000
32	19	200,000
33	20	200,000
34	21	200,000
35	22	200,000
36	23	200,000
37	24	
38	25	
39	26	
40	27	
41	28	
42	29	
43	30	

Figure 8. User input tab landfill site and waste acceptance data.

The following cells are optional but improve the accuracy and usefulness of the model if the cell is filled (Figure 9):

44	N.B. For tables below enter the average values for the year of analysis only.	
45	Landfill Gas	
46	Total Landfill Gas Output (m^3/yr)*	25,000,000
47	Methane Content (%)	
48	Methane Output (m^3/yr)	12500000
49		
50	Waste Characteristics	
51	Potential Methane Generation Capacity (m^3/Mg)*	100
52	Moisture Content (%)	40
53	Temperature (°C)	30
54		
55	Leachate	
56	pH	7.2
57	COD (mg/L)	6,000
58	BOD 5 day (mg/L)	180
59	BOD/COD ratio	0.08
60	Alkalinity as $CaCO_3$ (mg/L)	700
61	Chloride (mg/L)	1000
62	Ammonia-N (mg/L)	750
63	Iron (mg/L)	17
64	Zinc (mg/L)	0.1
65		

Figure 9. User input tab for landfill gas generation waste characteristics, and leachate data.

If data for a particular box is missing it can be left blank. However, the DST will provide more accurate results with a complete dataset. The remaining cells are automatically calculated by the tool:

- Methane Output (m^3/yr)
- Age of site at year of analysis (years)

3.3.3 Comparing multiple sites

The process is then repeated in columns C-F for additional sites 2-5 (Figure 10 and Figure 11). Data can be entered for each landfill site for waste input, leachate, waste and gas characteristics tables. A maximum of five sites can be entered in one calculation. At the bottom of the table in the user input tab, left click on the “Calculate Scores” button to view the results of the tool (Figure 11).

	A	B	C	D	E	F
4	Name of Landfill Site	1	2	3	4	5
5						
6	Waste Input					
7	Landfill Open Year* (YYYY)	1986	1998	2005	1992	1989
8	Closure Year (YYYY)	2009				2006
9	Year of Analysis* (YYYY)	2012	2012	2012	2012	2012
10	Age of site at year of analysis (years)	26	14	7	20	23
11	Accepted Waste Mass (tonnes)*					
12	YEAR					
13	0	200,000	50,000	150,000	10,000	100,000
14	1	200,000	20,000	150,000	20,000	100,000
15	2	200,000	30,000	150,000	30,000	100,000
16	3	200,000	100,000	150,000	40,000	100,000
17	4	200,000	90,000	150,000	50,000	100,000
18	5	200,000	106,000	150,000	60,000	100,000
19	6	200,000	122,000	150,000	70,000	100,000
20	7	200,000	138,000	150,000	80,000	100,000
21	8	200,000	154,000	150,000	90,000	100,000
22	9	200,000	170,000	150,000	100,000	100,000
23	10	200,000	186,000	150,000	110,000	100,000
24	11	200,000	202,000	150,000	120,000	100,000
25	12	200,000	218,000	150,000	130,000	100,000
26	13	200,000	234,000	150,000	140,000	100,000
27	14	200,000	250,000	150,000	150,000	100,000
28	15	200,000	266,000	150,000	160,000	100,000
29	16	200,000	282,000	150,000	170,000	100,000
30	17	200,000	298,000	150,000	180,000	
31	18	200,000	314,000	150,000	190,000	
32	19	200,000	330,000		200,000	
33	20	200,000	346,000		210,000	
34	21	200,000	362,000		220,000	
35	22	200,000	378,000		230,000	
36	23	200,000	394,000		240,000	
37	24		410,000		250,000	
38	25		426,000		260,000	
39	26		442,000		270,000	
40	27		458,000		280,000	
41	28		474,000		290,000	
42	29				300,000	
43	30				310,000	

Figure 10. Comparing multiple sites in the user input tab.

N.B. For tables below enter the average values for the year of analysis only.						
Landfill Gas						
Total Landfill Gas Output (m^3/yr)*	25,000,000	20,000,000	5,000,000	5,000,000	3,000,000	
Methane Content (%)		44	54			
Methane Output (m^3/yr)	12500000	8800000	2700000	2500000	1500000	
Waste Characteristics						
Potential Methane Generation Capacity (m^3/Mg)*	100	100	100	100	100	Help
Moisture Content (%)	40	50	60	70	10	
Temperature (°C)	30	30	50	10	10	
Leachate						
pH	7.2	8.1		6.4	7.5	
COD (mg/L)	6,000	3,000	5,000	2,000	5,000	
BOD 5 day (mg/L)	180	180		200		
BOD/COD ratio	0.08	0.04	0.05	0.03	0.07	
Alkalinity as $CaCO_3$ (mg/L)	700	600	900	700	600	
Chloride (mg/L)	1000		3000	4000	2000	
Ammonia-N (mg/L)	750	700	800	900	1000	
Iron (mg/L)	17	11		1	18	
Zinc (mg/L)	0.1	0.2	0.1	0.3		
			CALCULATE SCORES			

Figure 11. User Input tab displaying calculate scores button.

4 Understanding the results: Landfill methane generation scores calculation

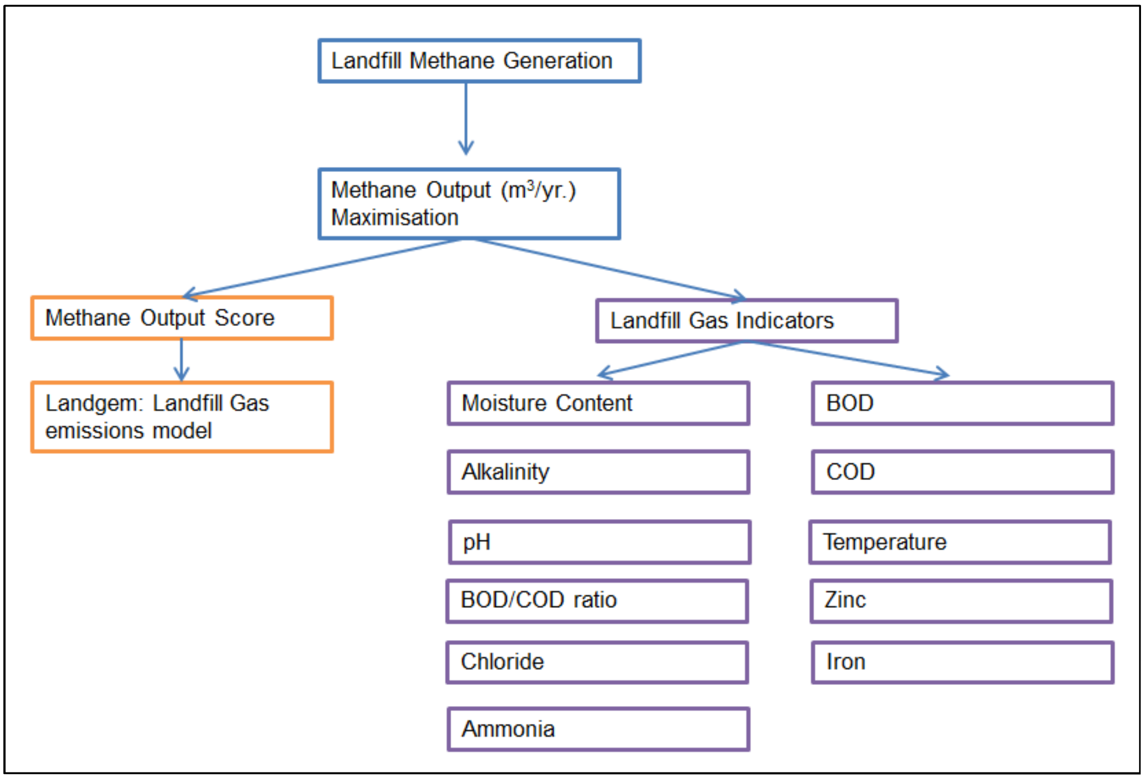

Figure 12. The landfill methane generation is made up of the methane output score and the landfill gas indicators score.

The landfill methane generation is assessed by two scores (Figure 12) described in more detail below. A green, yellow and red traffic light system is used to indicate good, average and poor scores. The first score assesses the actual methane output rate for each site against what rate is predicted for that site using the United States Environment Protection Agency (USEPA) landfill gas model, LandGEM (US EPA, 2005). The second score assesses the landfill environment by scoring each landfill gas indicator against the ideal range for that indicator for methane generation. In this way, the methane output score is the primary source of assessment for each landfill site and the landfill gas indicator score provides a secondary insight into why a landfill may have good, average or poor methane generation. Each indicator is given a score which, if red, suggests that it is negatively influencing methane generation.

4.1 Methane Output Score

$$M_{x,t} = \frac{B_A - B_I}{B_I} \tag{4-1}$$

Where M is the methane output score for site ‘x’ at time ‘t’, ‘B_A’ the actual methane output (m^3/yr) and ‘B_I’ the ideal value for methane output (m^3/yr).

The methane output score is calculated by comparing the predicted methane output rate to the actual methane output rate for a given site. The methane output is predicted using the LandGEM model described below. The score is expressed as the percentage deviation from the predicted value. Therefore, a score of 0% represents the actual methane output being equivalent to predicted output. The methane output score is given a red, yellow or green traffic light to highlight good, average or poor methane output rate (Table 4).

Table 4. A description of the traffic light system boundaries for the methane output score.

Traffic Light	Score Boundary (% deviation from LandGEM prediction)	Description
Green	Greater than >30%	Good performance - methane output is currently at or higher than predicted levels, no action necessary.
Yellow	Between -30% and 30%	Average performance - methane output is currently below predicted levels and close monitoring of red and yellow landfill gas indicators is necessary.
Red	Less than -30%	Poor performance - methane output is currently well below predicted levels, remedial action is necessary for red and yellow landfill gas indicators.

4.2 Landfill gas models

Landfill gas (LFG) emissions are routinely calculated but not always measured directly. The decomposition of waste in landfills and the resultant methane and landfill gas emissions are predicted with the help of models which summarise the very complex chemical and biological reactions involved. Several models of varying levels of complexity with different orders of kinetics have been developed, namely zero-order, first-order and second order models as well as some more complex models (Kamalan et al., 2011). Landfill gas prediction is currently known as unreliable and inaccurate due to wide variance in results between different models and between prediction and actual results (Scharff and Jacobs, 2006). The prediction of emissions can be used in a DST to measure the difference between expected and actual values. Landfill gas prediction is important both to address environmental issues of greenhouse gas emission and to predict future income from the sale of energy from landfill gas by operators.

The most popular models have been the first order models and overviews and formulae for the most used first order models (GasSim, LandGEM, TNO, Afvalzorg and EPTR) are presented by Kalaman et al. (2011) and Thompson et al. (2009). There are a variety of factors influencing the generation of LFG and methane. The three key factors for methane generation models for a landfill site are (Thompson et al., 2009):

1. the amount of waste disposed since commissioning
2. the degradable organic fraction
3. the decay rate (of each fraction and as a whole).

As many old landfills (pre-2005) do not hold records of waste quality or quantity the composition of the waste is not always known and therefore estimations and extrapolations are necessary in many cases. More recently, the IPCC guidelines (2006) establish a method that can be applied to all countries/regions and provides default values (e.g. regional generation rates), estimates and calculation methods to overcome lack of historical data (IPCC, 2006). However these estimates introduced higher uncertainty in the final results and sites with poor management data have the highest uncertainties in their calculations. Uncertainties have been traced back to the lack of data with regards to the amount and composition of the waste, but also to assumptions that have to be used such as decomposition rates, methane generation rates, oxidation rate and capturing efficiency among others. In addition the overall rate of LFG emission can be influenced by operational interventions like waste compaction, leachate recirculation or aerobic landfilling and theoretically these factors should also be taken into consideration when modelling generation.

The main criticism of methane prediction models is their lack of accuracy and validation (Thompson et al., 2009; Bogner and Matthews, 2003). Therefore, simple models are preferred (Oonk, 2010). Additional factors contribute to the inaccuracy of models including the percentage of landfill gas lost to the atmosphere and the percentage methane content. Models including GasSim and LandGEM assume 50% of landfill gas is methane but this has been proven to vary on landfill sites (US EPA, 2005; Golder Associates, 2013). Each model is limited by the assumptions made. A major assumption is that there is a direct relationship between carbon degradation and biogas output even though it is known that inhibition plays an important role. Improvements may be made to the models in the use of more accurate kinetic values and the inclusion of other substrates including proteins and lipids.

This clearly highlights why methane generation models need to be validated (i.e. predicted methane has to be compared with methane recovery data). One of the more accurate methods to validate methane prediction models at landfill sites is the carbon balance approach (Spokas et al., 2006).This approach takes into account that methane generated can be oxidised recovered and stored within the landfill site. It can also migrate and only the remaining amounts are emitted into the atmosphere. Each component of the carbon balance can be quantified, modelled, optimised and engineered to reduce the amounts of amounts of methane emitted and maximise LFG collection

Methane potential (L_0) is an important parameter in most models which is defined as the total methane produced by waste over its lifetime. This can be calculated by finding the amount of waste (W) and the concentration of dissolved organic carbon (DOC). The DOC is calculated from the fractionation of waste e.g. percentage garden waste, food waste. However, a proportion of organic carbon is non-degradable and needs to be accounted for by the factor DOC_f. DOC_f is a constant between 0.4 and 0.7 in most models. Methane potential is thus calculated as:

$$L_0 = 1.33 \times W \times DOC \times DOC_f \quad \textbf{(4-2)}$$

The methane potential is then used in a given function to predict its release over time (Table 5). The time taken for its release is determined by the half-life, or k-value. The lower the half-life or higher the k-value, the shorter time it takes for methane to be released (Table 5). The k-value is therefore the decay rate constant. A first order decay model, as used by the US EPA in their LandGEM model assumes that the majority of gas will be emitted immediately and with gradually decline over time (US EPA, 2005). However, in reality, landfill gas production has a lag time after the landfill is covered and closed which is not included in the model. The time taken to produce landfill gas varies from months to years and is dependent on a wide range of factors including climate and waste quality (Gregory et al., 2003; IPCC, 2006; Robinson, 2007). Models can incorporate this by assuming a zero gas production for a given period of time at the start. Another problem with these models is that they assume that gas production is uniform throughout a landfill waste mass when in reality some areas may have access to oxygen, be saturated with leachate or subject to toxic conditions which would reduce gas production. Therefore a methane correction factor can be used to adjust for this (Oonk, 2010).

$$G = WL_0ke^{-kt} \tag{4-3}$$

G Methane production rate (m^3/yr)

W Annual waste acceptance rate (tonnes/yr)

Lo Ultimate methane yield m^3/tonne

k Decay rate constant

Table 5. A comparison of methane potential and half-life values used in landfill gas models for MSW. Adapted from Oonk, (2010).

Model	L0 (kg/tonne)	Half Life (Yr)
IPCC	63	12-23 (slow)
		7 (moderate)
		4 (fast)
GasSim	51	15 (slow)
		9 (moderate)
		6 (fast)
LandGEM	122 (CAA)	14 (conventional)
	72 (inventory)	35 (arid)
E-PRTR (France)	55	5-10

The CAA values in LandGEM are based on US federal values for the Clean Air Act (CAA) and are used to determine whether a landfill site meets these regulations. The inventory values are used for sites where no specific site data is available and is based on the USEPA Compilation of Air Pollutant Emission Factors (AP-42).

As waste is generally added to landfill over a number of years, multiple equations are used to sum the methane emissions from each section of waste. This model is criticised as it produces a discrete value each year, rather than the continuous amount observed (Oonk, 2010). This means that landfill gas emissions are underestimated. LandGEM has been updated to address this issue by calculation methane emissions for every tenth of the year to increase the landfill gas estimate (Reinhart et al., 2005).

$$G = (W/10)L_0ke^{-kt} \quad \textbf{(4-4)}$$

Multi-phase models specify degradation k values for different waste types, such as food waste degrading faster than newspaper. This approach assumes that waste types do not affect each other (are independent) in landfill degradation unlike the simplified first order decay model above. Higher quality and quantities of data are necessary for this type of model which is typically unavailable to landfill operators (Oonk, 2010). All landfill gas models are subject to a degree of error and through the propagation of errors in the amount of carbon in the waste, degradable carbon content, methane correction factor and assumed methane content a figure of 20-40% (Oonk, 2010).

The authors have therefore chosen a simpler model over a multi-phase model. The LandGEM model is used in the DST to predict methane output over time for each site. The tool can be adapted to use a different model if necessary.

4.3 LandGEM Landfill gas model predictions for sites 1, 2, 3, 4 & 5

The landfill gas model “LandGEM” has been used to predict LFG production or potential methane generation capacity for up to five sites (US EPA, 2005). The methane calculation worksheet is used from the original LandGEM model. The calculation feeds from the user input age, waste acceptance and potential methane generation capacity (L_0). The default parameters for a conventional landfill (inventory) are used:

Decay rate constant: $k = 0.04$

Potential methane generation capacity: $L_0 = 100\ m^3/Mg$

However, LandGEM assumes all waste accepted into the landfill site is MSW which is not necessarily the case. Therefore the potential methane generation capacity value can be altered by the user depending on the composition of waste if known.

Also shown for each site is the predicted methane emissions over time in graphical format. The actual methane emissions are also shown to aid comparison between prediction and real values (Figure 13). This helps the user to identify any under/overestimation by the LandGEM model. A table is also provided adjacent to the graph for the user to manually input historical LFG production into the graph for further comparison as only one year is analysed in the DST.

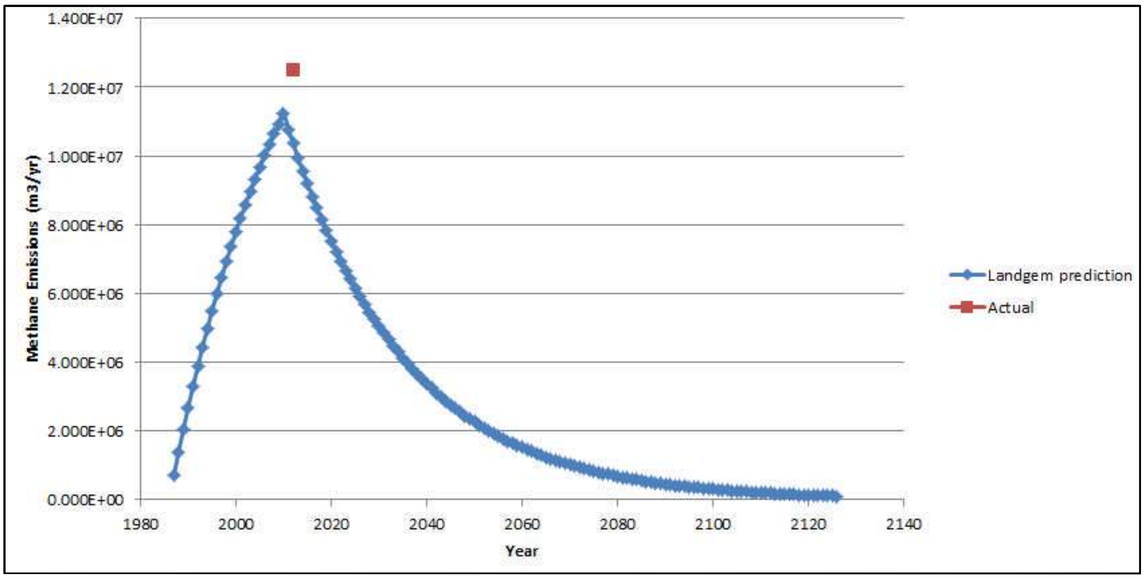

Figure 13. LandGEM tab displaying the actual methane output and prediction for site 1 in a graphical format.

4.3.1 LandGEM parameters

The decay rate constant (k=0.04) is set in the DST however the potential methane generation capacity can be changed by the user. A default value of 100 m^3/ Mg is provided if the value is unknown. If the L_0 value is known, the user can enter this value into the user input tab. A waste composition with a higher cellulose content has a higher L_0 value and therefore produces a higher methane output. A guide is provided as background for a range of L_0 values used in the LandGEM model based on wet bioreactor, conventional landfills and CAA regulatory values (Figure 14).

Potential Methane Generation Capacity (m^3/Mg)	USEPA Landfill Type
50	
60	
70	
80	
90	
96	Inventory - Wet Bioreactor
100	Inventory - Conventional (Default Value)
110	
120	
130	
140	
150	
160	
170	CAA Conventional

Figure 14. LandGEM parameters tab showing the potential methane generation values that can be selected by the user.

4.4 Landfill Gas Indicator Score - Multi-criteria decision analysis

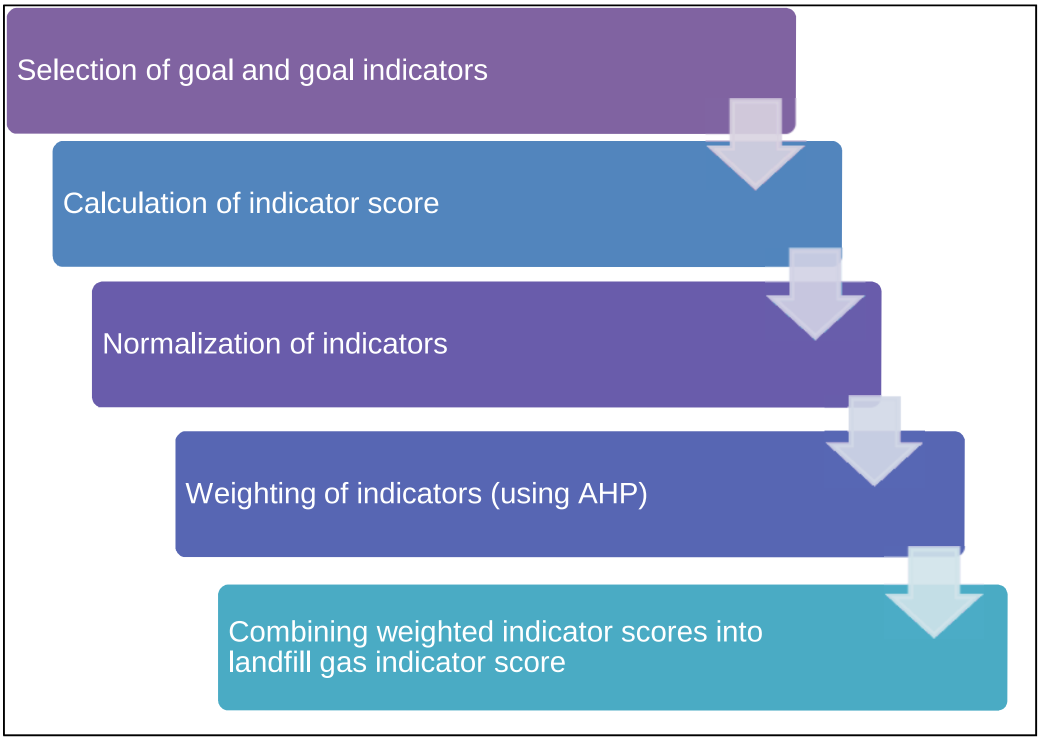

Figure 15. The procedure for calculating landfill gas indicator scores in the DST using multi-criteria analysis (AHP: Analytical Hierarchical Process).

The second element of the DST is to calculate a score for the landfill gas indicators (Figure 12). A multi-criteria decision technique is used to combine the scores of the landfill gas indicators. In order to achieve the aim of an understandable tool, the method used by (Krajnc and Glavič, 2005a; Krajnc and Glavič, 2005b) was followed (Figure 15). This method provides a mathematically transparent composite index score by combining key measurable leachate, waste and biogas parameters and comparing those to ideal values.

Multi criteria analysis (MCA) (or multi criteria decision analysis) is essential for the use of a decision support tool in a landfill situation due to the wide range of processes and parameters involved. The analysis has the ability to combine information associated with each option by setting universal criteria including costs, benefits and stakeholder opinion in order to assess the most preferred option (Huang et al., 2011). It is a widely used method in modern policy decision making in order to identify the most preferred option, to highlight the presence of options or to rank options (Dodgson et al., 2009). Large aspects of the analysis are decided by the decision makers including the selection of options and criteria, weighting and performance scores which has positive benefits including the ability to produce a situation specific tool and the application of professional knowledge. The technique implicitly requires these decisions to be highlighted and replicated. However, flaws in the technique emerge with the introduction of systematic bias from the decision maker and the inability to encompass different viewpoints (Dodgson et al., 2009). Scores for each option based on the set out criteria are normalized in order to compare them across different units and are presented in a performance matrix. Dodgson et al. (2009) highlight that criteria and options need to be finite and as few as is reasonably possible in order to limit the data gathering and processing necessary.

There are many different methods of MCA but all are based on the data gathered in the performance matrix. Methods include multi attribute utility theory and a linear additive model. The analytical hierarchical procedure is the most common in environmental science literature MCA accounting for half of 312 papers studied (Huang et al., 2011). The authors relate this dominance to the method's availability of expertise and software comparative to other techniques. A direct analysis of the performance matrix can be performed whereby professional knowledge is used to view the option which out competes all others, if possible. However, this lacks reproducibility and scientific basis. Dodgson et al. (2009) states the following criteria necessary for the selection of an appropriate MCA method:

1. Internal consistency and logical soundness
2. Transparency
3. Ease of use
4. Data requirements not inconsistent with the importance of the issue being considered

5. Realistic time and manpower resource requirements for the analysis process
6. Ability to provide an audit trail, and
7. Software availability, where needed.

4.4.1 Gas, waste and leachate ideal values

Gas, waste and leachate datasets are necessary for the DST multi criteria analysis to compare actual values to what is expected for each indicator. The datasets are provided in the DST to show the ideal values within which a landfill is expected to produce an optimal methane output rate (Table 2). These are the range of observed values for each parameter used in the decision support tool. Actual and ideal values are compared by percentage deviation from the ideal values according the stage the landfill site has entered e.g. acetogenic or methanogenic. The model allows for ideal values to be updated as new data comes to light.

4.4.2 Indicator selection

Table 6. Landfill gas indicators selected for the DST and omitted.

Landfill Gas Indicator	
Selected	**Omitted**
Moisture Content	Waste Density
Temperature	Waste Composition
pH	Nutrient Ratio
COD	Microbial population
BOD 5 day	Sulphate
BOD/COD ratio	Other heavy metals
Alkalinity as $CaCO_3$	
Chloride	
Ammonia-N	
Iron	
Zinc	
Ammonia-N (mg/L)	
Iron (mg/L)	
Zinc (mg/L)	

The indicators were selected according to their influence on methane generation as discussed in the "Theory" section and the availability of measured data for that indicator published in literature. Table 6 shows which indicators have been selected for the DST and which have not been included.

4.4.3 Calculating individual landfill gas indicator scores and normalizing the indicator values

The landfill gas indicator score is calculated for each individual indicator on an unweighted basis. The score is normalized against the average ideal value and lower boundary of the ideal value range in order to compare and aggregate different units. The ideal values for each indicator are given in Table 1 and Table 2.

$$I_{N,it} = \frac{I_{A,it} - I_{V,i}}{I_{V,i} - I_{L,i}} \qquad \textbf{(4-5)}$$

Where $I_{N,it}$ is the normalized indicator *I* for time t and I_A is the actual indicator value, I_V is the average ideal value and I_L is the lower boundary of the ideal value range.

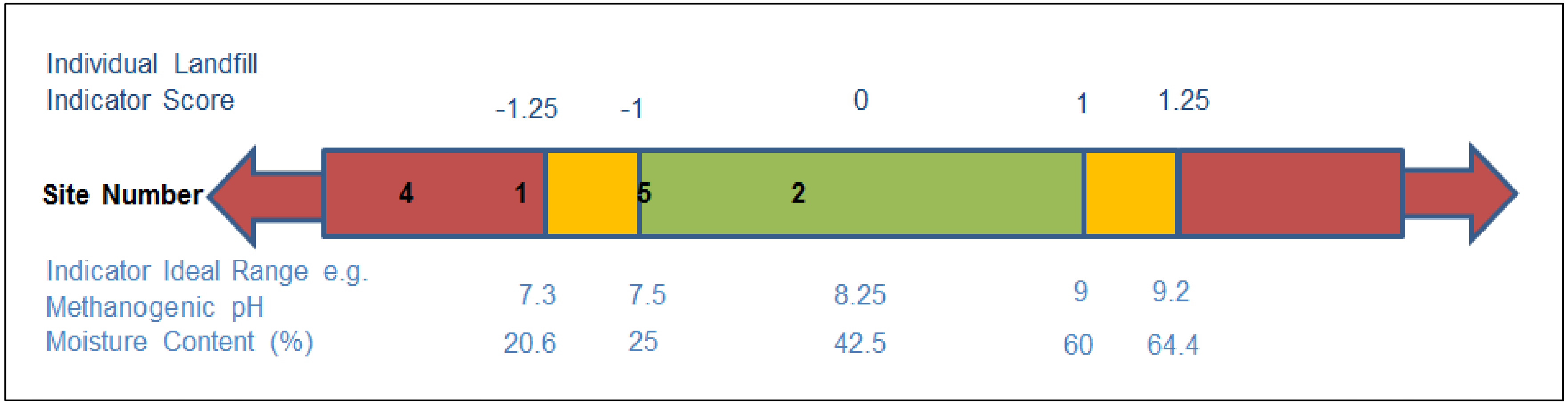

Figure 16. An example of the traffic light system for the two landfill gas indicators. The scores reflect the proximity of the user input value for each site to the ideal average value relative to the size of the ideal range.

It is important that the score is relative to the size of the boundary as a small change in one indicator could have a much larger effect than another if the boundary was smaller. The scores are given red, green and yellow traffic light symbols within the DST which are dependent on the boundary levels for the scores set (Figure 16 and Table 7). The boundary levels are based on the ideal value range for each indicator. So, for pH in methanogenic conditions the ideal lower and upper values are 7.5 and 9 and these values are hence the boundaries for the green traffic light. The values are normalized using equation (4-5) to give scores of -1 and 1 for the lower and upper boundaries. Hence, the average ideal value, for methanogenic pH this is 8.25 is assigned a score of 0. The yellow zone encapsulates a score greater than 1 and -1 but less than 1.25 and -1.25. For the methanogenic pH indicator this is 7.3 – 7.5 and 9-9.2 respectively. Scores greater than this on both positive and negative scales are given a red traffic light.

Table 7. A description of the traffic light system for individual and total landfill gas indicator scores. Boundary levels are set by the ideal range for each indicator.

Traffic Light	Score Boundary	Description
Green	Between -1 and 1.	Indicator is within accepted range for good methane production.
Yellow	Between -1.25 and -1 and between 1 and 1.25.	Indicator is outside the accepted range and close monitoring is necessary.
Red	Greater than -1.25 and greater than 1.25.	Indicator is well outside the accepted range and remedial action is necessary.

4.4.4 Calculating the total weighted landfill gas indicator score

4.4.4.1 Normalizing the indicators

The indicators are normalized during the procedure to calculate individual landfill indicator scores.

4.4.4.2 Weighting

Each parameter is then weighted according to its influence on the required objective such as pH having a high influence on the goal of methane maximisation. There are many different methods of weighting parameters or indicators such as multi attribute utility theory and a linear additive model (Dodgson et al., 2009). The analytical hierarchical process (AHP) was chosen which provides a straightforward and fast method of calculating the relative weights of each parameter (Krajnc and Glavič, 2005b; Krajnc and Glavič, 2005a). This also allows the user to amend the weights of the parameters if necessary. This technique is widely used in MCA processes (Contreras et al., 2008). Similar benefits and costs of this technique occur as with MCA such as the ability to apply situation specific professional knowledge but with the bias involved in allowing the decision maker to decide which parameter is more important than others.

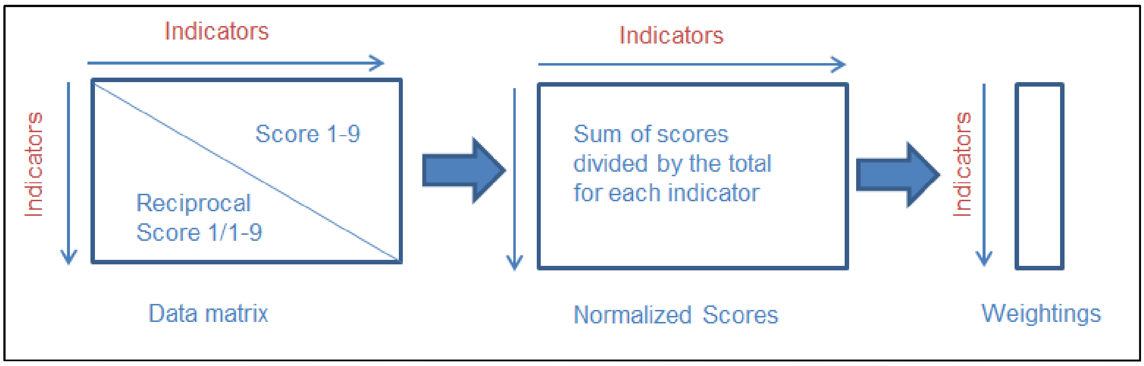

Figure 17. The analytical hierarchical process calculation for weighting parameters influencing methane output.

The analytical hierarchical process (AHP) uses a linear additive model which gives a value score for an option for each criterion, multiplies this by the weight of the criteria and sums the scores together (Saaty, 1987) (Figure 17). The AHP varies from other linear additive models by using pairwise comparison of criteria to assign weights (Saaty, 1987; Vaidya and Kumar, 2006).

WEIGHTING CALCULATION

Landfill Indicators

	Moisture Content (%)	Alkalinity as $CaCO_3$ (mg/L)	pH	BOD/COD ratio	COD (mg/L)	BOD 5 day (mg/L)	Temperature (°C)	Zinc (mg/L)	Iron (mg/L)	Chloride (mg/L)	Ammonia - N (mg/L)
Moisture Content (%)	1	2	3	4	5	5	6	9	9	9	9
Alkalinity as $CaCO_3$ (mg/L)	0.5	1	3	4	5	5	5	7	7	7	8
pH	0.333333333	0.33333333	1	3	4	4	5	7	7	7	8
BOD/COD ratio	0.25	0.25	0.33333333	1	3	3	4	6	6	6	6
COD (mg/L)	0.2	0.2	0.25	0.33333333	1	2	3	5	5	5	5
BOD 5 day (mg/L)	0.2	0.2	0.25	0.33333333	0.5	1	3	5	5	5	5
Temperature (°C)	0.166666667	0.2	0.2	0.25	0.33333333	0.33333333	1	3	3	3	3
Zinc (mg/L)	0.111111111	0.14285714	0.14285714	0.16666667	0.2	0.2	0.33333333	1	1	1	0.2
Iron (mg/L)	0.111111111	0.14285714	0.14285714	0.16666667	0.2	0.2	0.33333333	1	1	1	0.2
Chloride (mg/L)	0.111111111	0.14285714	0.14285714	0.16666667	0.2	0.2	0.33333333	1	1	1	0.16667
Ammonia - N (mg/L)	0.111111111	0.125	0.125	0.16666667	0.2	0.2	0.33333333	5	5	6	1
TOTAL	3.094444444	4.73690476	8.58690476	13.5833333	19.6333333	21.1333333	28.3333333	50	50	51	45.5667

Figure 18. Default scores (1-9) from the pairwise decision during the AHP process for landfill gas indicators. Numbers below 1 represent the reciprocal score (reverse) for each pairwise decision.

A pair wise decision is made between each parameter on a scale: 1 being the parameters are equivalent in their indication of objective and 9 being parameter 1 is 9 times more important than parameter 2 (Contreras et al., 2008). The reciprocal value (e.g. 1/9) is used for the relative indicator score in reverse. In other words, how many times more important to methane output is the row parameter over the column parameter. The assumption is made that when reversing the question, the value is also reversed e.g. 9 becomes 1/9. The tool then calculates the weights automatically by calculating the score relative to the sum of all scores for that parameter and averaging them out (Figure 18 and Figure 19). The total sum of weights must equal one (equivalent to 100%).

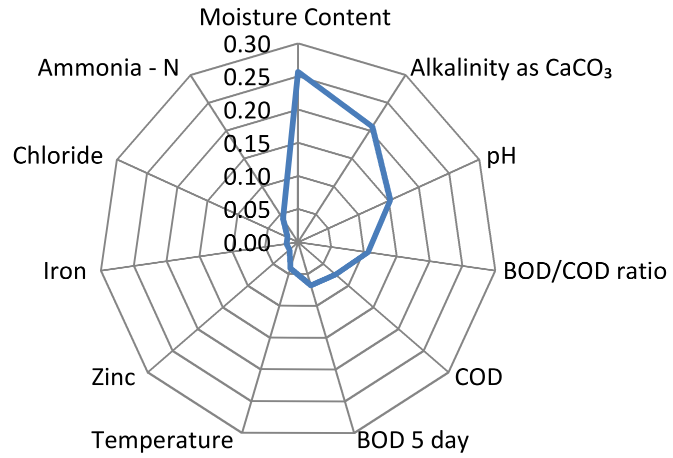

Figure 19. The default weightings assigned to each landfill gas indicator in the DST using the AHP technique.

Default scores from 1-9 for each indicator are provided but can be updated by the user according to site specific information of landfill gas indicator influence on methane generation (Figure 18). Default values are defined based on academic research and professional knowledge of landfill site management which is highlighted in the landfill gas theory section.

4.4.5 Combining the weighted scores

The individual landfill gas indicator scores are multiplied by the weighting for each indicator, given an absolute value and summed to give the total weighted landfill gas indicator score for each site. This provides a useful summary of how much the site varies from ideal values for methane generation over all indicators. The weighted scores are given an absolute value before being summed so as to show the total deviation from the ideal which is not negated by negative values. If positive and negative scores were summed there is potential for each score to cancel each other out to the average ideal value score (0) even if not the case.

$$Total\ Landfill\ Gas\ Indicator\ Weighted\ Score = \sum_{it}^{n} W_i \times \left| I_{N,it} \right| \tag{4-6}$$

$$\sum_{i}^{n} W_i = 1$$

$$W_i \geq 0$$

Where:

I: Individual landfill gas indicator score

N: Normalized indicator

W: Weighting

T: Time

5 Viewing and interpreting the Results

5.1 Results Table

Each site is given a methane output score which records the percentage deviation from expected methane output to actual (Figure 20).

	Cell Name	1	2	3	4	5
5						
6	**Methane Output Score (%)**					
7	Methane Output	44.8%	60.9%	-7.2%	-57.7%	-57.5%
8						
9	**Landfill Gas Indicator Scores**					
10	Moisture Content	-0.1	0.4	1.0	1.6	-1.9
11	Alkalinity as $CaCO_3$	1.0	0.0	3.0	1.0	-4.0
12	pH	-1.4	-0.2 #		-2.5	-1.0
13	BOD/COD ratio	0.2	-0.2	-0.1	-0.3	0.1
14	COD	1.5	0.0	1.0	-0.5	1.0
15	BOD 5 day	0.0	0.0 #		0.1 #	
16	Temperature	0.0	0.0	2.0	-2.0	-2.0
17	Zinc	-0.3	-0.2	-0.3	-0.2 #	
18	Iron	0.0	0.0 #		-0.1	0.0
19	Chloride	-0.5 #		0.4	0.9	-0.1
20	Ammonia - N	0.0	0.0	0.1	0.1	0.2
21	**Total Landfill Gas Indicator Score (weighted and absolute)**	0.6	0.2	1.1	1.2	1.6
22						
23			REMEDIES			

Figure 20. Results tab display.

Key:

	Good performance - methane output is currently at or higher than predicted levels, no action necessary
	Average performance - methane output is currently below predicted levels and close monitoring of red and yellow environment indicators is necessary
	Poor performance - methane output is currently well below predicted levels, remedial action is necessary for red and yellow environment indicators
	Indicator is within accepted range for good methane production
	Indicator is outside the accepted range and close monitoring is necessary
	Indicator is well outside the accepted range and remedial action is necessary. Click on "Remedies" tab.
#	No data entered in "User Input" tab for this cell.

Figure 21. The DST results tab key to symbols used in the traffic light system.

1	1 Age:	26				
Parameter	**Ideal Average**	**Ideal Range**	**Actual**	**Deviation from Ideal Average Relative to Ideal Range**	**Weight**	**Score**
Landfill Gas						
Methane Output (m^3/yr)	10,356,453	-	15,000,000	44.8%	-	0.4
						0.4
Landfill Gas Indicators						
Moisture Content (%)	43	35	40	-0.1	0.26	0.0
Alkalinity as $CaCO_3$ (mg/L)	600	200	700	1.0	0.21	0.2
pH	8	2	7	-1.4	0.15	0.2
BOD/COD ratio	0.06	0.20	0.08	0.2	0.11	0.0
COD (mg/L)	3,000	4,000	6,000	1.5	0.07	0.1
BOD 5 day (mg/L)	180	530	180	0.0	0.07	0.0
Temperature (°C)	30	20	30	0.0	0.04	0.0
Zinc (mg/L)	1	4	0	-0.3	0.02	0.0
Iron (mg/L)	15	277	17	0.0	0.02	0.0
Chloride (mg/L)	2,120	4,350	1,000	-0.5	0.02	0.0
Ammonia - N (mg/L)	740	2,150	750	0.0	0.04	0.0
Total Indicator Score						0.6

Figure 22. The DST calculation tab displaying how scores are calculated in the results tab.

For site 1, the methane output is above predicted levels and therefore it receives a green traffic light tick in the purple row (Figure 20). A score of 44.8% shows that it is operating at 44.8% higher levels of methane output than predicted in the LandGEM model. Therefore, using the key provided to understand the traffic light symbols, no action is necessary to remediate the site (Figure 21). The detailed calculation is shown below and in the “Calculation” tab (Figure 22):

$$M_{x,t} = \frac{B_A - B_I}{B_I} \tag{5-1}$$

Where M is the methane output score for site x at time t, B_A is the actual methane output (m^3/yr) is and B_I is the ideal value for methane output (m^3/yr).

$$\frac{15{,}000{,}000 - 10{,}356{,}453}{10{,}356{,}453} = 44.8\% \tag{5-2}$$

In order to understand what is happening within the landfill environment to achieve this score a breakdown of landfill gas indicators is provided in the rows below (Figure 20). Landfill gas indicators including pH, temperature and moisture content are given a separate score based on the deviation from the ideal average score set out in leachate and waste dataset tabs and is relative to the size of the ideal range. An indicator weighted total of the absolute scores provide the total deviation from the ideal average value based on a multi criteria analysis where each indicator is weighted according to its impact on methane production. Hence, the sum of the weighted score in the row named “total landfill gas indicator score” does not match the sum of the unweighted environment indicator scores.

For site 1, most indicators are operating within the accepted range for optimal methane output. For example, a moisture content of 40% gives a score of -14.3% below the ideal average value for optimal methane output relative to the range of the ideal value for that indicator. The calculation is shown below and in the calculation tab (Figure 22):

$$I_{N,it} = \frac{I_{A,it} - I_{V,i}}{I_{V,i} - I_{L,i}} \tag{5-3}$$

Where $I_{N,it}$ is the normalized indicator *I* for time t and $I_A$is the actual indicator value, I_V is the average ideal value and $I_L$is the lower boundary of the ideal value range.

$$\frac{40 - 42.5}{42.5 - 25} = -14.3\% \tag{5-4}$$

Alkalinity is given a yellow traffic light which indicates that this indicator is just outside the ideal range for methane output and needs to be monitored (Figure 20). COD and pH are given a red traffic light which indicates that they are well outside the ideal range of 7.5-9 as indicated in Table 2 and action needs to be taken to address this issue.

The hyperlink for each parameter provides suggestions of solutions to improve the parameter score. A key is also provided to the right of the worksheet which instructs the user what to do in the case of red, yellow and green lights (Figure 21). The "#" symbol is used to show where no user input has been found. The yellow "REMEDIES" button can be clicked to show remedies for problems with each of the parameters (Figure 20).

The total landfill gas indicator score uses multi criteria analysis to sum the individual indicator scores. As each indicator has a different effect on the methane output, each indicator is given a weight to represent this difference (Figure 22). The weighting technique is described in the weighting section above and in the "Weighting" tab. Each weighted score is given an absolute value (no negative values) to sum the total deviation from the ideal relative to the size of the ideal range.

5.2 Results Graph

The methane output scores for each site are automatically displayed in the “Results” tab in graphical format to aid comparison between sites and over time (Figure 23).

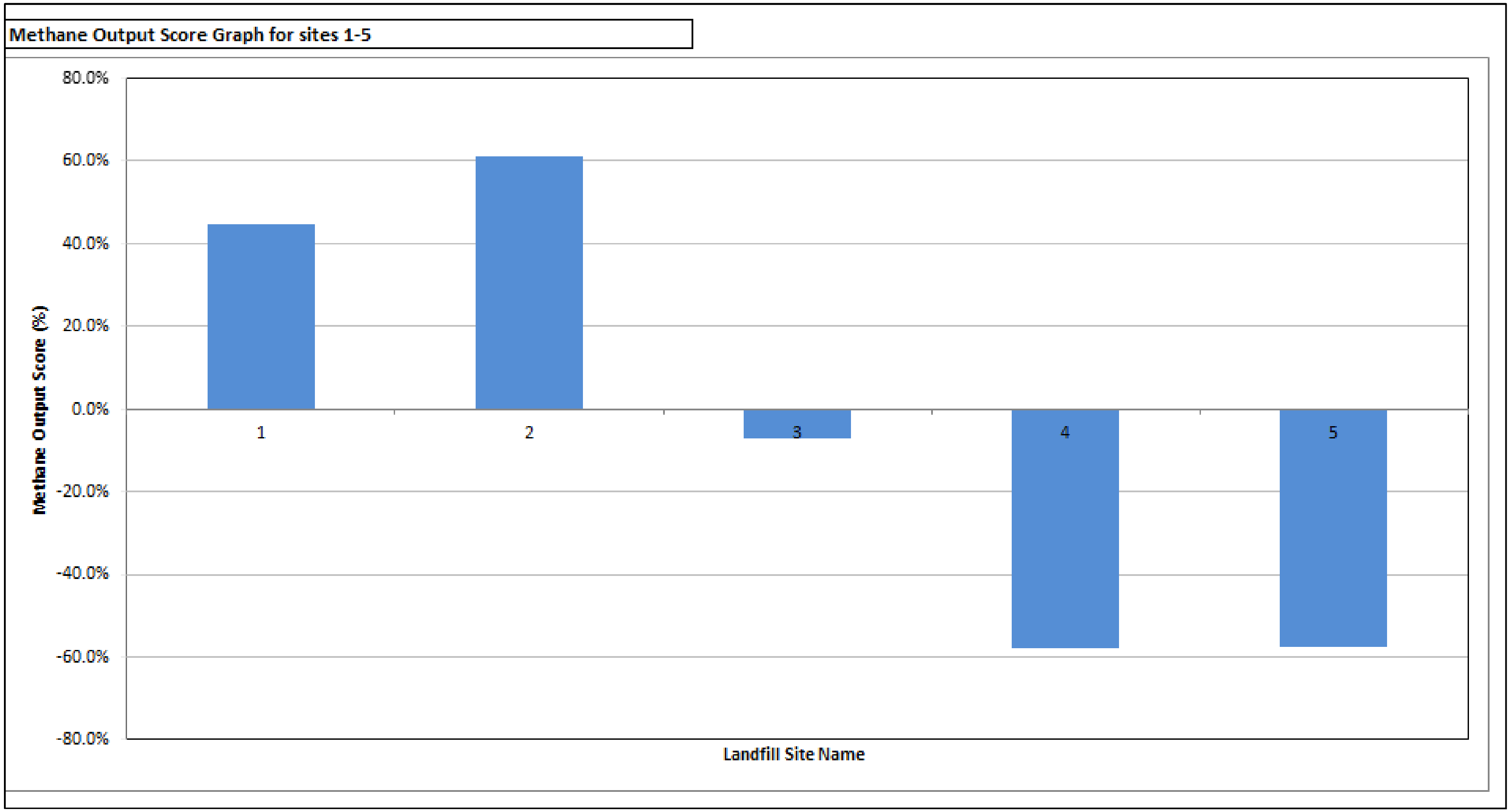

Figure 23. Results tab total landfill score graphical display.

5.3 Remedies for landfill gas enhancement

The remedies worksheet gives details of the cause, effect and potential remedies for parameters which fall outside of the optimal range for methane output (Figure 24 and Figure 25). Each parameter occupies one row. The source of the recommendation is also given (Figure 26). The worksheet is designed to aid understanding and highlight potential remedies and is not designed for detailed, site specific technical advice. Further management advice would need to be sought.

BOD/COD ratio	Ratio of biologically degradable to chemically oxidisable substrate. Lack of biodegradable substrate or an inhibited biodegradation process.

Figure 24. Remedies tab showing BOD/COD ratio indicator score cause.

Adjust waste input or consider alternative parameters for methanogenesis inhibition. Microbial seeding from sewage/ AD sludge. Introduction of gravel to increase surface area for microbial growth.

Figure 25. Remedies tab showing potential remedies for BOD/COD ratio with a red traffic light.

Mata Alvarez (2003)

Figure 26. The source for each remedy is given in the "Remedies" tab.

In the case of site 1, although the overall landfill score and weighted environmental indicator score has a green traffic light, some environmental indicators display red and yellow lights which can be addressed if wanted. This is due to the fact that methane generation is a complex and dynamic process which does not require all indicators to be green to produce green traffic lights. The user can identify the indicator in the column labelled "Indicator" such as BOD/COD ratio and read along the row for cause, effect and potential remedies. The BOD/COD ratio remedy encompasses the remedies needed for both BOD and COD indicator issues.

The COD indicator describes the amount of chemically oxidisable material in the leachate. Higher COD can be expected in a landfill where waste has been buried for more than 26 years. This could be due to a problem within the landfill in the ability to degrade material but as the BOD and BOD/COD ratio scores are green this may indicate an error in the data provided.

6 Cautionary Notes

The DST provides a framework for the assessment of landfill methane generation. It has been designed to allow the user to adjust the settings due to the heterogeneous nature of landfill sites. For example, the methane potential in the landfill gas model can be adjusted to reflect specific site waste inputs. Also, the weightings of the landfill gas indicators can be altered to reflect landfill operator professional knowledge of which indicator affects landfill gas generation more than others at one site. Therefore, caution must be taken to note that with different model settings, the results are not comparable and advice for remediation is not necessarily supported by the authors. Several limitations are highlighted below which the user needs to be aware of when reviewing the tool results. Conservative estimates must be used in order to not overestimate methane generation.

6.1 Tool Limitations

- Any lack in data quantity or quality reduces the reliability and increases the error of the decision support tool.
- A user changing the model settings needs to be a professional and knowledgeable of landfill processes.
- Once a landfill site or cell is capped and closed, it is not re-opened which would allow oxygen into the site and hence disrupt the methanogenesis process.
- Landfill sites or cells average leachate, waste and gas measurements are assumed to be representative of the entire landfill site.

- Atypical waste input increases the tools inaccuracy as the landfill gas predications are based on typical inputs.
- Landfill leachate is assumed to develop from acetogenic to methanogenic conditions within 2 years (World Bank - ESMAP, 2004).
- Landfills have not reached an aerobic stage and are less than 40 years old.

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ABBREVIATIONS

AHP	Analytical Hierarchical Process
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DST	Decision Support Tool
E-PRTR	European Pollutant Release and Transfer Register
IPCC	Intergovernmental Panel on Climate Change
LandGEM	Landfill Gas Emissions Model
LCFA	Long Chain Fatty Acid
MCA	Multi-criteria analysis
MSW	Municipal Solid Waste
US EPA	United States Environment Protection Agency
VFA	Volatile Fatty Acid

GLOSSARY OF TERMS

Anaerobic Digestion	The biodegradation of organic material by microorganisms in the absence of oxygen to produce methane and carbon dioxide gas. The biodegradation takes place through a number of stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis.
Analytical Hierarchical Process	An MCA approach to mathematically define preferences for a set of criteria/indicators. This technique is used to provide weightings for the importance of each criterion on the pre-assigned objective of the MCA (Saaty, 1980). The user must define how much more important one criterion is over another on a scale of 1-9 in a series of pairwise comparisons. The question prescribed is “How many more times more important is criteria A over criteria B?” Reciprocal values are used automatically for the reverse comparison of criteria i.e. B over A.
Decay rate constant (k)	The decay rate constant determines the rate of release of the methane potential within a landfill site in first order decay models such as LandGEM. It is a function of environmental conditions within the landfill such as pH, temperature and moisture. Within the models its value remains constant over time.
Decision support tool	Decision support tools are “documents or software produced with the aim of supporting decision making i.e., something that carries out a process in decision making” (Bardos et al., 2002).They provide a robust, consistent, transparent and reproducible method for the decision making process (Sorvari and Seppälä, 2010).
Ideal Value	The value or range of values of a specific waste, gas or leachate parameter within which methane output from landfill sites is expected to be optimised.
Indicator	One of a set of measures to assess the achievement of the overall objective.
Landfill Gas	The product of the biodegradation of waste in landfills. The gas consists mainly of carbon dioxide and methane but also contains nitrogen and other trace gases.
Landfill Gas Indicator Score	This score provides an indication how far the landfill gas indicator values within the landfill environment varies from the ideal range for each indicator to produce an optimal methane output rate. The weighted sum of the percentage deviation of the actual indicator value from the average ideal value of that indicator relative to the

	range of the ideal value at the specified point in time.
Landfill methane generation	Within this tool and manual, landfill methane generation is defined as methane output rate achieved by a landfill site. Methane is used as the most valuable product of landfill processes to a landfill operator. Two scores are used to measure landfill methane generation: the methane output score and the landfill gas indicator score.
Methane Output Score	This score provides an indication of how well a landfill site is producing methane gas. The percentage deviation of actual methane output rate from the predicted value for each landfill site at the specified point in time. The prediction in this DST is provided by LandGEM.
Multi-criteria analysis	Any method to analyse the preferences within a set of options to achieve one or multiple overall objectives. Often used when monetary data is unavailable or inappropriate.
Overall Objective	The overall goal of the MCA and against what each indicator is measured.
Potential Methane generation capacity(L_0)	The methane generation potential is a constant which determines the potential for a landfill site to produce methane. It has a positive relationship with the amount of cellulose present in the waste to biodegrade into methane.